D6.2

Assessment of Traffic Management Procedures in Transition Areas

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Executive Summary

This Deliverable 6.2 of the TransAID project presents and evaluates the simulation results obtained for the scenarios considered during the project’s first iteration. To this end, driver- and AV-models designed in WP3, traffic management procedures developed in WP4, and V2X communication protocols and models from WP5 were implemented within the iTETRIS simulation framework. Previous main results from Deliverable 4.2, where baseline and traffic management measures without V2X communication were compared, have been confirmed. While not all scenarios’ traffic KPIs were affected, the realistic simulation of V2X communication has shown a discernible impact on some of the TransAID traffic scenarios, which makes it an indispensable modelling aspect for a realistic performance evaluation of V2X traffic scenarios. Flaws of the proposed traffic management algorithms concerning wireless V2X communication and the accompanying possibility of packet loss have been identified and will be addressed during the project’s second iteration. Finally, lessons learned while working on these simulation results and assessments have additionally been described in the form of recommendations for the real-world prototype to be developed in WP7.

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1 Introduction

1.1 About TransAID

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

There will be areas and situations on the roads where high automation can be granted, and others where it is not allowed or not possible due to missing sensor inputs, high complexity situations etc. At these areas, many automated vehicles will change their level of automation. We refer to these areas as “Transition Areas”.

TransAID develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of automated, connected, and conventional vehicles, especially at Transition Areas. A hierarchical approach is followed where control actions are implemented at different layers including centralised traffic management, infrastructure, and vehicles.

First, simulations are performed to examine efficient infrastructure-assisted management solutions to control connected, automated, and conventional vehicles at Transition Areas, taking into account traffic safety and efficiency metrics. Then, communication protocols for the cooperation between connected/automated vehicles and the road infrastructure are developed. Measures to detect and inform conventional vehicles are also addressed. The most promising solutions are then implemented as real world prototypes and demonstrated at a test track and during the second iteration possibly under real urban conditions. Finally, guidelines for advanced infrastructure-assisted driving are formulated. These guidelines also include a roadmap defining activities and needed upgrades of road infrastructure in the upcoming fifteen years in order to guarantee a smooth coexistence of conventional, connected, and automated vehicles.

Iterative project approach

TransAID will perform its development and testing in two project iterations. Each project iteration lasts half of the total project duration. During the first project iteration, the focus is placed on studying Transitions-of-Control (ToCs) and Minimum Risk Manoeuvres (MRMs) using simplified scenarios. To this end, models for automated driving and ToC/MRM are adopted and developed. The simplified scenarios are used for conducting several simulation experiments to analyse the impacts of ToCs at TAs, and the effects of the corresponding mitigating measures.

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

1.2 Purpose of this Document

Simulations performed and evaluated within the TransAID project until today have covered baseline scenarios providing reference values for different performance indicators in the absence of traffic management procedures (see [1]), and prototypic simulations including traffic management procedures developed in WP4 (see [2]). However, in favour of a rapid proof of concept, communications between vehicles and road side infrastructure were disregarded, so far. This approach allowed a quick and basic evaluation of the proposed traffic management procedures. Still, to obtain a more realistic simulation and performance evaluation, the integration of V2X communication is crucial as the wireless propagation of data packets introduces further challenges to the scenarios considered in TransAID in the form of information delay, error, or loss.

This Deliverable presents the results obtained from a comprehensive simulation study of the scenarios defined in TransAID's first iteration, including realistic communication models. To allow for this, a continuous integration of all relevant components of the open-source simulation framework iTETRIS was performed. The framework's basic (and open-source) components consist of the microscopic traffic simulator SUMO, the communication network simulator ns-3, as well as the middleware iCS. These basic components were augmented by continuous input from WPs 3, 4, and 5 in the form of driver- and AV-models (WP3), traffic management procedures (WP4), and communication protocols (WP5), respectively, yielding a realistic simulation environment setup. Throughout the continuous integration of these parts, a test suite was utilised to simultaneously monitor the correct operation of the coupled simulation components.

This Deliverable gives a detailed documentation of the results obtained by the fully integrated simulations. Its focus is on the differences in the performance measures for the different scenarios resulting from difference between realistic and ideal communications. In addition to this assessment of communication impacts for all scenarios, the Deliverable also expresses recommendations for the virtual prototypes to be implemented in WP7.

1.3 Structure of this Document

The rest of this report is structured as follows: the general set-up of the simulation environment common to all scenarios is described in Section 2. This includes the configuration of traffic scenarios, details on communication simulation, and an overview of the processing toolchain for the simulation results' impact assessment. Section 3 comprises scenario-specific simulation environment parameters as well as the presentation of respective simulation results along with interpretation and discussion. Conclusions of these results are then drawn in Section 4, complemented with recommendations for the virtual prototypes.

1.4 Glossary

Abbreviation/Term	Definition
ACC	Adaptive Cruise Control
AD	Automated Driving
ADAS	Advanced Driver Assistance Systems
API	Application Programming Interface
AV	Automated Vehicles
C-ITS	Cooperative Intelligent Transport Systems
C2C-CC	Car2Car Communication Consortium
CAM	Cooperative Awareness Message
CAV	Cooperative Automated Vehicle
CPM	Collective Perception Message
CV	Cooperative Vehicle
DENM	Decentralised Environmental Notification Message
DX.X	Deliverable X.X
ERTRAC	European Road Transport Research Advisory Council
ETSI	European Telecommunications Standards Institute
GUI	Graphical User Interface
HMI	Human Machine Interface
iCS	iTETRIS Control System
ITS	Intelligent Transport System
ITS-G5	Access technology to be used in frequency bands dedicated for European ITS
LDM	Local Dynamic Map
LOS	Level Of Service (from Highway Capacity Manual)
LV	Legacy Vehicle

MCM	Manoeuvre Coordination Message
MRM	Minimum-Risk Manoeuvre
No-AD zone	No-Automated-Driving zone
OMNeT	Objective Modular Network Testbed
OSI	Open Systems Interconnection
PDR	Packet Delivery Ratio
RAT	Radio Access Technology
RSI	Road-Side Infrastructure
RSU	Road-Side Unit
SAE	Society of Automotive Engineers
SUMO	Simulation of Urban MObility
TA	Transition area
TCI	Task Capability Interface
TM	Traffic Management
TMC	Traffic Management Controller
TOR	Take-over Request
ToC	Transition of Control
TraCI	Traffic Control Interface
TransAID	Transition Areas for Infrastructure-Assisted Driving
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-anything
VMS	Variable Message Signs
WP	Work Package
XML	Extensible Markup Language

2 Simulation Setup

2.1 Configuration of Traffic Scenarios

The simulations presented in this document are extensions of previously performed simulations taken out under more ideal assumptions to allow a rapid testing and prototyping of traffic management solutions (see [2]). The enhancements move the extended simulations of this report towards greater realism and mainly concern the modelling and implementation of the V2X communication processes necessarily involved in a real-world deployment of the proposed traffic management measures. While the simulations presented in [2] have assumed ideal communications, the extended simulations consider individual messages and simulate their transmission and reception with a high level of detail (see Section 0). Previous simulations modelled message exchanges as immediate and loss-free transmissions of any information that needed to be exchanged between connected vehicles and the infrastructure, resp. traffic management (e.g., the triggering of takeover requests), or as a direct inspection of the required data as obtainable from the simulation software (e.g., the position and speed of vehicles from SUMO). Currently, we have implemented the traffic management obtaining the information used in the algorithms from sources, which can be conceived to possess a real counterpart, such as V2X messages or road side detectors, e.g., induction loops or traffic surveillance cameras.

For the basic setup of the scenarios, we have employed the demand configurations and simulation networks that have been already employed for the previous simulations (see [1] and [2]). Where necessary, we have included additional RSUs and detectors into the networks for retrieving information previously obtained directly from the simulation and for the spatial reference of participating nodes in the communication processes.

The implementation of traffic management applications employing realistic information retrieval and advice transmissions was implemented within the iTETRIS simulation platform, which has been extended for these purposes (see [3]). The development of iTETRIS applications in C++ closely followed the idealised implementation for the previous simulations, which were scripted in Python. This involved a two-step process: firstly porting the traffic management logic and SUMO interfacing into the C++ app so as to replicate the logic implemented previously, and secondly restructuring the obtained application to depict the communication processes.

During the second step of the application development, we first assumed ideal communications by employing the LightComm communication mockup module to facilitate the testing of the protocol. The corresponding setup was used to obtain a baseline for the assessment of the impact, which realistic communication processes have upon the functioning of the devised traffic management measures.

2.2 Simulation of Communications

The extended simulations described in this document include the realistic simulation of the communications between vehicles, and between vehicles and the infrastructure. The here presented have been conducted using the iTETRIS platform [4] which is been evolved extended within the framework of the TransAID project. The complete simulation framework iTETRIS platform is shown in Figure 1

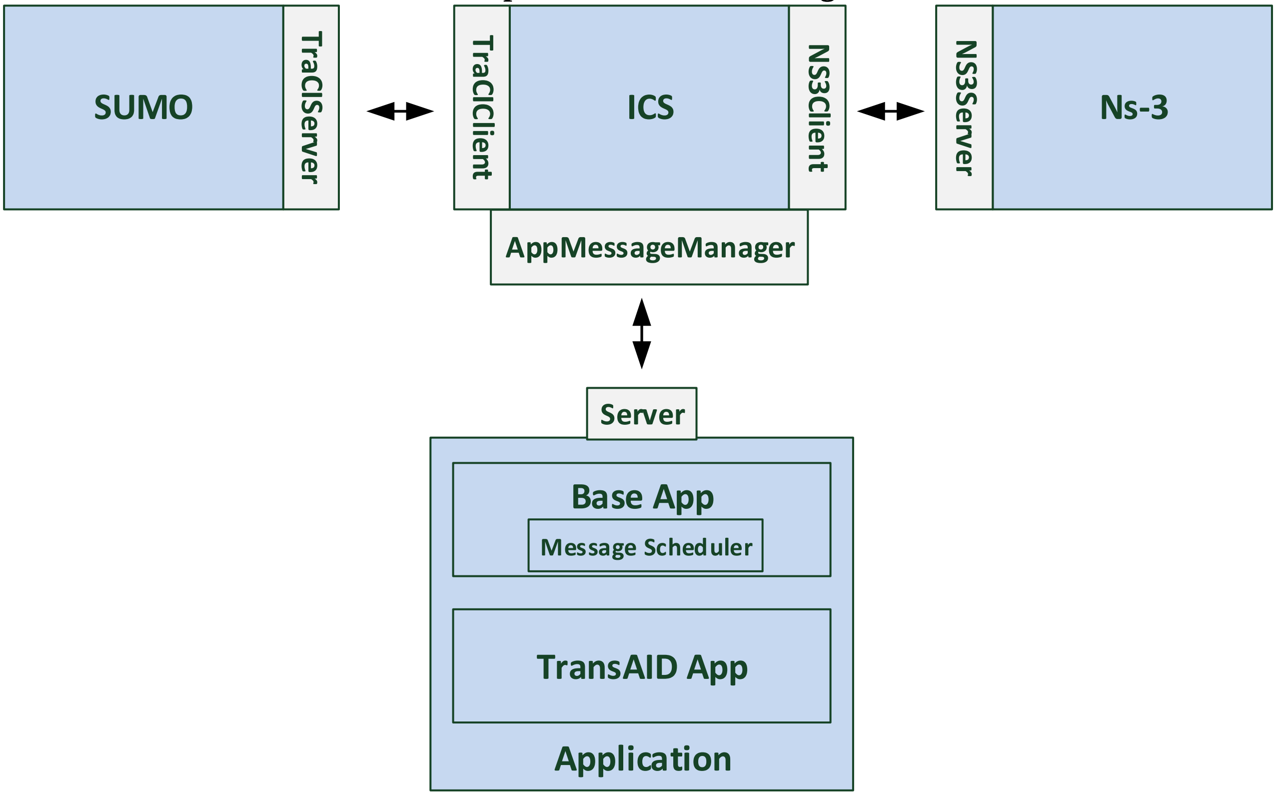


Figure 1**Error! Reference source not found.**. A detailed explanation about the different modules that integrate iTETRIS can be found in [1]. Compared to the simulations presented in [2], this new set of simulations include a new module, the ns-3 simulator [5], to model realistic V2X communications. Ns-3 is a discrete-event network simulator which includes models for simulating the ITS-G5 architecture. The specific parameter configuration of ns-3 can be found in Section 2.2.2. Note that the communications range of vehicles and RSUs is not provided as it will depend on the specific scenario (e.g. the level of interferences can reduce the communication range). In addition, to generate simulations that can serve as a baseline for comparison, the iTETRIS platform can use the designed LightComm communications simulator [1]. LightComm is a mockup module that substitutes ns-3 and models ideal communications. The LightComm module will assume that all messages generated by the applications are successfully received if the distance between the transmitter and receiver is lower than a predefined threshold of 1500 meters. We have selected this threshold taking into account the following requirements: a) The threshold should be higher than the maximum distance in which the TransAID services need to deliver information and b) the threshold should be low enough to avoid the unnecessary reception of messages of no interest (i.e. a CAM message of a vehicle situated 5 km away) that will increase the simulation time. Note that this threshold can be configured based on the application requirements.

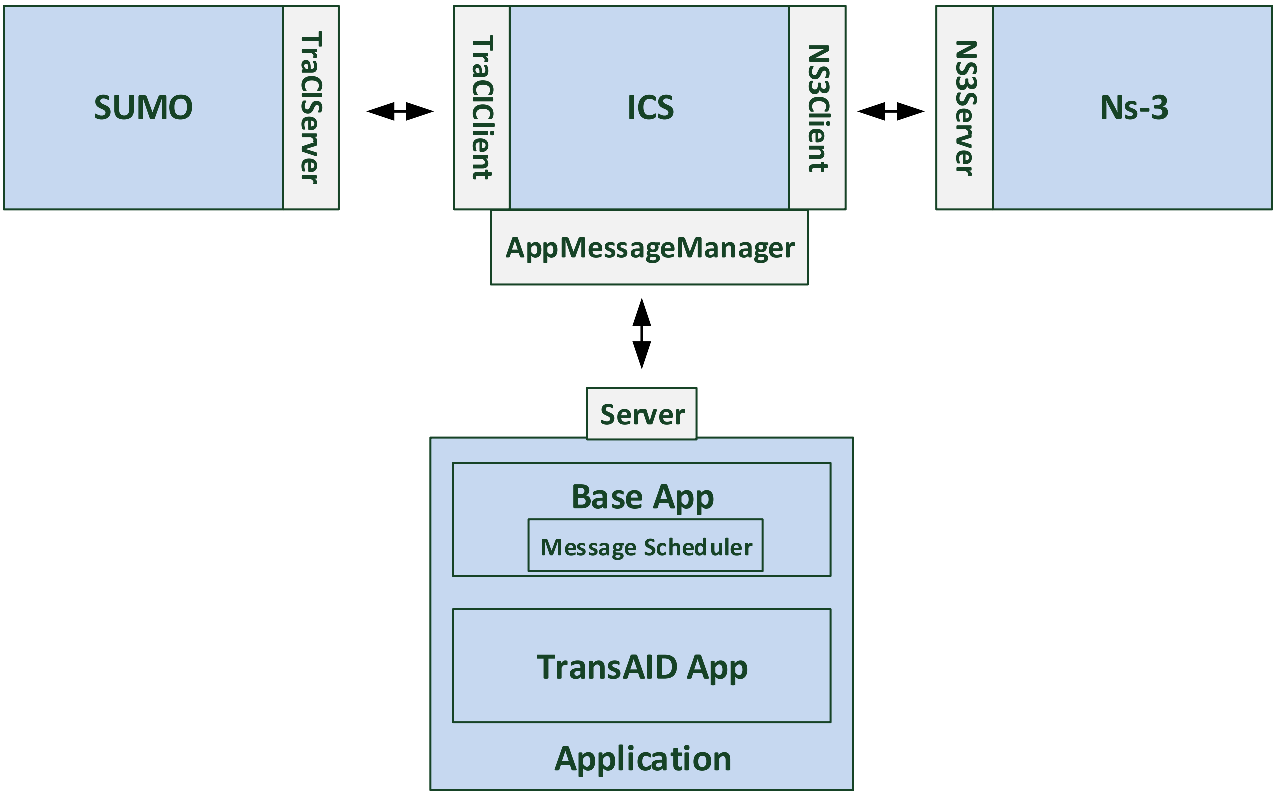


Figure 1: TransAID iTETRIS simulation framework.

The iTETRIS platform has been also extended to include the TransAID applications (application module in Figure 1); applications are the implementation of the TransAID services [2]. It is important to note that the implemented TransAID applications take into account the transmission and reception of V2X messages. In particular, the applications process the received V2X messages and based on their content they schedule the transmission of new V2X messages or command to the vehicles the execution of a specific manoeuvre (e.g., after the reception of a ToC advice, the application will command a take-over request to the driver of the vehicle). To facilitate the design and implementation of the TransAID applications in iTETRIS, the iTETRIS platform introduces a new functionality, the Message Scheduler (see Figure 1), which handles the dynamic transmission of periodic V2X messages such as CAM [6], CPM [7], and MCM [8]. The Message Scheduler periodically (every 100 ms following ETSI standards EN 302 637-2 [6] and TR 103 562 [7]) checks the generation rules of the different messages and schedules the messages whenever the triggering conditions are fulfilled.

2.2.1 CAV/CV Message Generation Rules

In the iTETRIS platform, the TransAID project implemented specific generation rules for the different V2X messages. These generation rules have been defined following the ETSI standards on ITS for the CAM and CPM messages [6], [7] and the TransAID work in WP5 for the case of the MCM [9]. It should be noted that different ITS stations (i.e. CV, CAV, etc.) implement different V2X messages following the message flow of the different TransAID Services defined in D5.2 [9]. In what follows, we describe the generation rules implemented in the iTETRIS platform for the different messages involved in the TransAID applications.

CAVs and CVs transmit CAM and MCM messages whenever one of the following conditions is fulfilled (as indicated above, these conditions are checked every 100 ms):

- The distance between the current position of the vehicle and the position included in the last transmitted message of the same class (i.e. CAM or MCM) exceeds 4 m.
- The absolute difference between the current speed of the vehicle and the speed included in the last transmitted message of the same class (i.e. CAM or MCM) exceeds 0.5 m/s.
- The time elapsed since the last transmitted message of the same class (i.e. CAM or MCM) exceeds 1 s.

The size of the CAM and MCM messages has been set to 190 bytes[1].

The transmission of CPM is slightly different, as the generation rules are based on the objects detected instead of on the dynamics of the ego-vehicle. Consequently, the CPM will be sent whenever a new object is detected or any of the following conditions are satisfied for a previously detected object:

- The absolute position of the object has changed by more than 4 m since the last time that the object was included in the CPM.
- The absolute speed of the object has changed by more than 0.5 m/s since the last time that the object was included in the CPM.
- The time elapsed since the last time that the object was included in the CPM exceeds 1 s.

All new detected objects and those that satisfy at least one of the previous conditions are included in the CPM. In order to limit the size of the CPM, the iTETRIS platform was configured to include up to 50 detected objects in each CPM. ETSI's work item 'DTR/ITS-00183' on collective perception service has recently indicated that the CPM could include up to 255 objects though [7]; this limit will be considered for the forthcoming simulations of the second iteration of the project. Anyway, for the scenarios considered in these simulations the average number of detected objects is below the configured limit. In this context, and contrary to the case of the MCM and CAM messages, the size of the CPM depends on the number of objects included in the CPM. All transmitted CPMs include the ITS PDU Header, the Management Container, and the Station Data Container. These three containers have each a size of 121 bytes. Additionally, the Sensor Information Container (35 bytes) is included once per second. The CPM also includes the detected objects in the Perceived Object Container (35 bytes per object). If no single object satisfies the CPM generation rules, the CPM is sent every second with the ITS PDU Header, the Management Container, the Situation Container and the Sensor Information Containers (i.e. 156 bytes).

In the implemented TransAID applications, in addition to the CAM, MCM, and CPM messages transmitted by the vehicles (i.e. CV and CAV) following the generation rules presented above, the infrastructure also transmits DENM, MCM, MAPEM, or IVIM messages. At the infrastructure side, the type and transmission frequency of the V2X messages depend on the specific TransAID service simulated. The specific message flow of each one of the TransAID services is defined in [9]. For the simulations presented here, we set the size of the messages transmitted by the infrastructure to 190 bytes, except for CPM messages due to their dynamic size.

2.2.2 Communications Parameters

Within the iTETRIS platform, the V2X communications are performed in the ns-3 simulator. This section details the configuration of the communications parameters used in ns-3. All CAVs and CVs are equipped with an ITS-G5 transceiver; they all operate in the same CCH channel at 5.9

[1] Note that the size of the messages described in this section refers to the size of the packets transmitted on the physical layer (of the OSI model).

GHz. The propagation effects are modelled using the Winner+ B1 propagation model following the 3GPP guidelines [10] and the EU delegated directive 2010/40/EU [11]. Table 1 summarises the communications parameters used in the ns-3 simulator.

Table 1: Communications parameters.

Parameter	RSU	CAV/CV
Transmit Power	18 dBm	22 dBm
Antenna gain	5 dBi	1 dBi
Antenna height	6 m	1.5 m
Channel bandwidth	10 MHz	
Carrier frequency	5.9 GHz	
Noise figure	9 dB	
Energy detection threshold	-85 dBm	
Data rate	6Mbps (QPSK 1/2)	

Further details on the simulated scenarios can be found in [2] which were initially described in [12]. It should be noted, that in the first iteration of the project, only traffic in the ongoing direction is considered. The simulations have been repeated for different LOS and different traffic mixes as described in [1].

2.3 Assessment

The simulations and the assessment of all iTETRIS scenarios presented within this report follow a common pattern of processing the simulation output. We expect that this pattern will again be applied within the second project iteration and probably in a very similar form in other projects employing the iTETRIS platform. Therefore, in this section we describe the corresponding toolchain, which effectively represents a practical user interface for performing large scale simulations involving iTETRIS applications.

The processing roughly follows these steps: a batch script manages and executes parallel iTETRIS simulations and collects the raw output generated. This raw output is aggregated to obtain KPIs (cf. [13]) for the simulated scenario. Based on the aggregated output, graphs are automatically generated (see Figure 2).

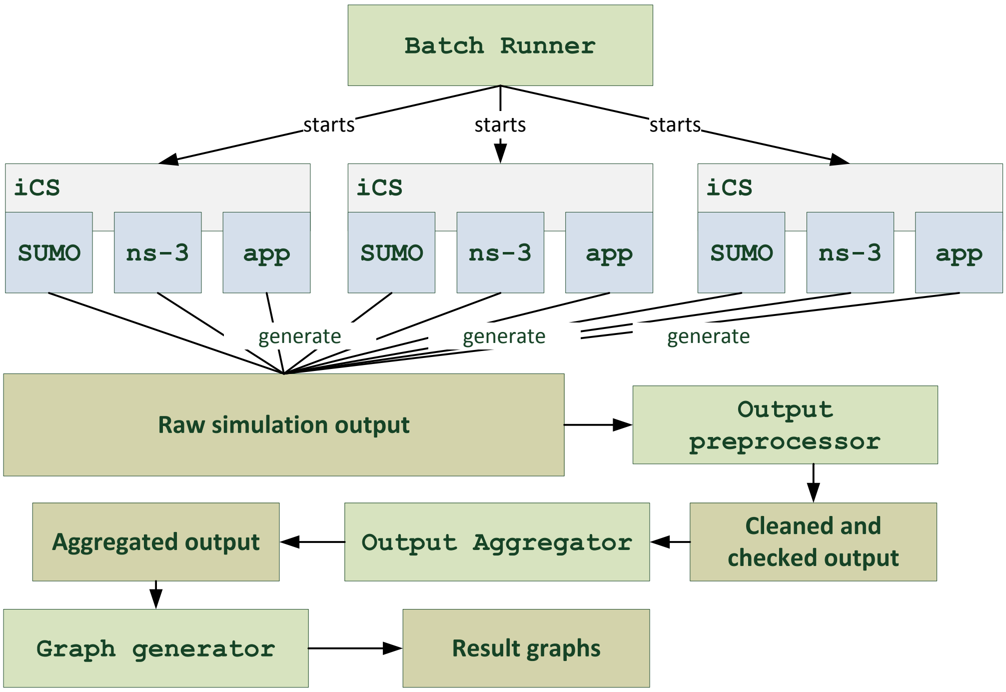


Figure 2: TransAID toolchain (overview of processing stages).

The preparation that needs to be done by the user consists of:

1. Configuring the batch script, which requires as input the parameter ranges for the traffic mix, demand level, and parametrisation scheme, as well as the amount of sample points (replications) per parameter combination.
2. Setting up the general scenario, i.e., the configuration templates for SUMO, ns-3, and possibly the traffic management application.

The batch script then creates a corresponding directory tree for the organisation of raw outputs, and copies filled configuration file templates into its leaves, preparing simulation environments for the individual simulation runs.

When the simulation batch has been finished, the output processing is started. In a first step, the relevant raw output data is copied and checked into a processing directory. An aggregation script then collects the disaggregated raw output per run and parameter combination. It results in one database containing information about KPIs for statistical processing as well as one with detector and trajectory data for spatio-temporal plots. Finally, another set of scripts performs the rendering of visualisations ready to be used in scientific reports.

3 Scenario Simulations

3.1 Scenario 1.1: Provide path around road works via bus lane

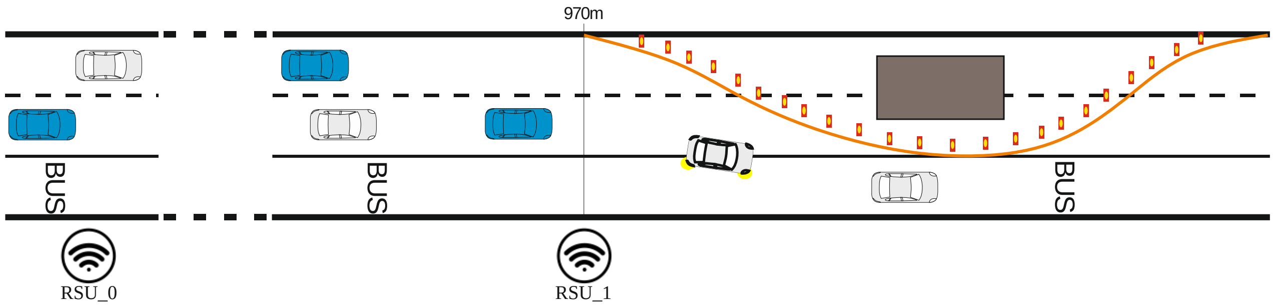


Figure 3: Schematic representation of Scenario 1.1.

3.1.1 Introduction

Scenario 1.1 consists of a three-lane urban road with road works blocking the way for vehicles on the two left-most lanes as defined in [12]. Such a road closure enables vehicles to use the bus lane, as seen in Figure 3, to drive around the work zone. C(A)Vs might not detect such a special case where road usage restrictions are lifted, thus leading to a ToC/MRM action. However, this can be avoided by providing appropriate path information to the C(A)Vs initiated by the TMC. The path information completes the C(A)Vs view of the situation and allows them to plan their path around the road works. In order to keep the traffic flow smooth, the TMC additionally advises C(A)Vs to increase their headways within the merging area in case there are vehicles present on adjacent lanes. This advice is reset as soon as the merging area has been passed by the respective vehicle.

Simulation results of [2] have shown that traffic efficiency is not impaired by a higher penetration rate of C(A)Vs operating with increased headways at the considered levels of service (LOS A, B, and C). Furthermore, traffic safety significantly improves with less take-over events.

Due to the explicit simulation of communication in this scenario, two RSUs were added. Since their communication range is limited, they were placed such that the relevant areas were covered, i.e. the approach to the road works and the merge area, ending and starting at distance 970 m from the entry point, respectively (cf. Figure 3). The first RSU (named "RSU_0") broadcasts the path information to incoming C(A)Vs, while the second RSU (named "RSU_1") sends the above-mentioned headway advices (cf. Figure 3). Their precise positioning can be gathered from Table 2.

Table 2: Placement of RSUs in Scenario 1.1.

RSU ID	Distance from entry point
"RSU_0"	650 m
"RSU_1"	970 m

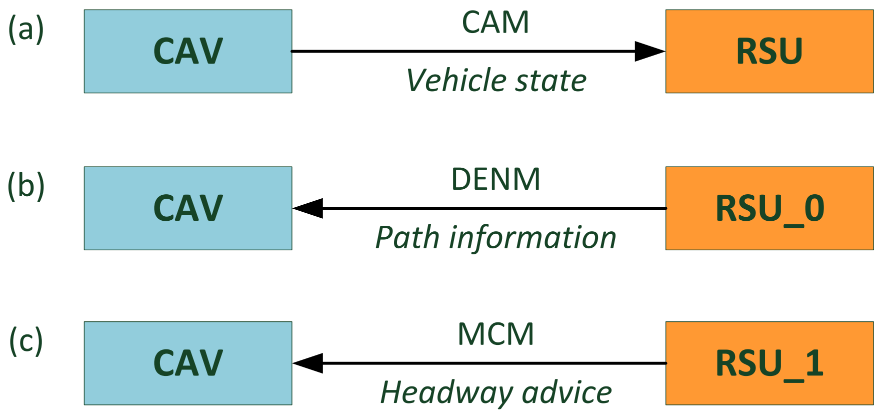


Figure 4: Communication overview of Scenario 1.1.

While for the base scenario in [2], we assumed a perfect and complete flow of information to implement the traffic management procedures, the addition of (wireless) communication to the scenario now leads to potential information loss and/or delay due to various factors affecting wireless communication signal propagation like attenuation, interference, reflection etc. Information, which was previously directly passed between the TMC and C(A)Vs, is now sent in the form of various message types (cf. Figure 4):

a) *Vehicle state* is periodically broadcast by CAVs to all RSUs in the form of CAM messages. The broadcast rate is proportional to the vehicle's speed but is set to a minimum of 1 second (cf. Section 2.2.1).
b) *Path information* is periodically broadcast every 2 seconds by RSU_0 to all CAVs as a DENM message, informing them to use the bus lane.
c) A *Headway advice* is sent by RSU_1 to a CAV in the merging area in the form of an MCM message (using the *Car Following Advice container*) in case earlier CAM messages have indicated that:
    - the CAV has entered it on the right-most lane and vehicles on the left lanes want to merge, or in case that
    - the CAV has left the merging area, respectively.

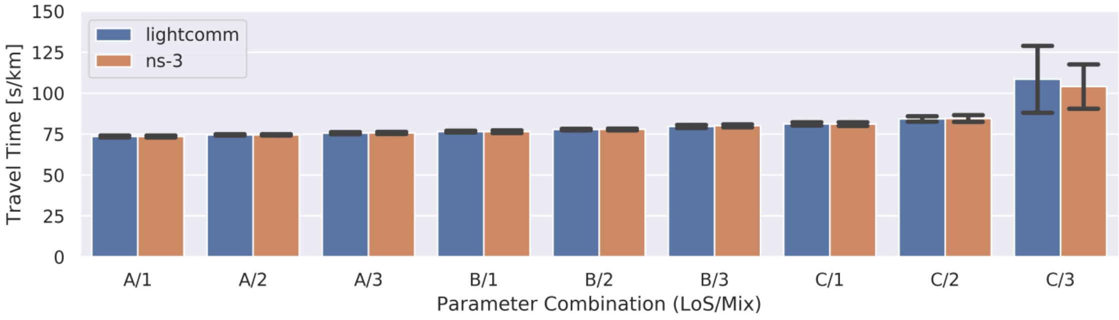
For more information on the protocol, see also [9]. The TMC is assumed to be reliably connected (by wire or similar) to both RSUs, such that all traffic management logic can be centrally processed, while still being able to differentiate the receiving RSU of incoming messages and distribute outgoing messages to the sending RSU accordingly. Even though CAM messages are received by all RSUs in range, these are only relevant when received by RSU_1 since the CAVs' position is mainly needed to derive the necessity of sending a headway advice to a CAV within the merging area. A ToC is initiated by the CAV itself as soon as its remaining distance to the road works undercuts a pre-defined threshold.

3.1.2 Results

In the following, we present the simulation results obtained for this scenario. The main goal of the assessment is to determine the robustness of the traffic management procedures with respect to the inclusion of realistic communication processes. Thus, we simulated all combinations of scenario parameters (demand level and distribution of automation capabilities) for ideal and for realistic communication as described in Section 0.

Traffic

As in Deliverable 4.2 [2], we inspected the performance aspects of traffic efficiency, traffic safety, and environmental impact, quantified with the network-wide traffic KPIs “travel time” and “throughput”, “critical events”, and “CO_2 emissions”, respectively (cf. [13]). Additionally, we inspected the number of TORs and MRMs, which are specific to TransAID.



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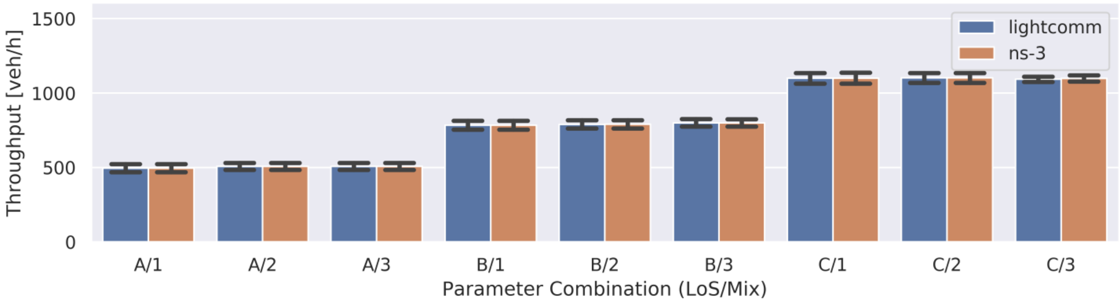

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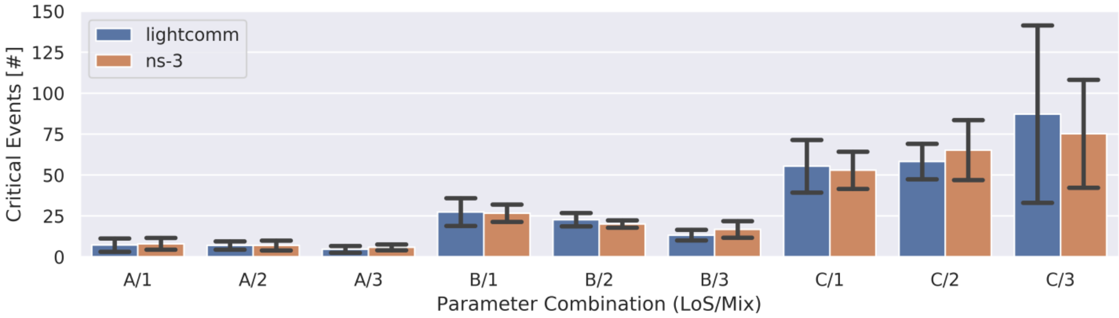

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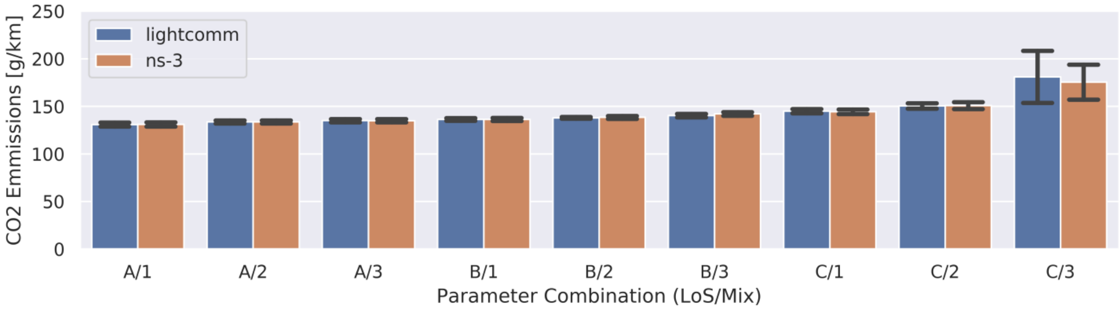
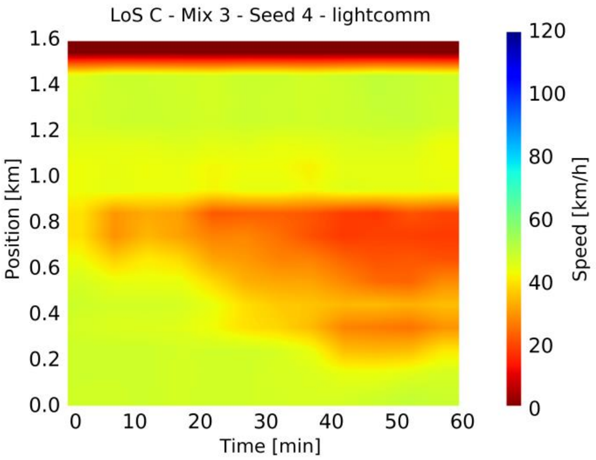


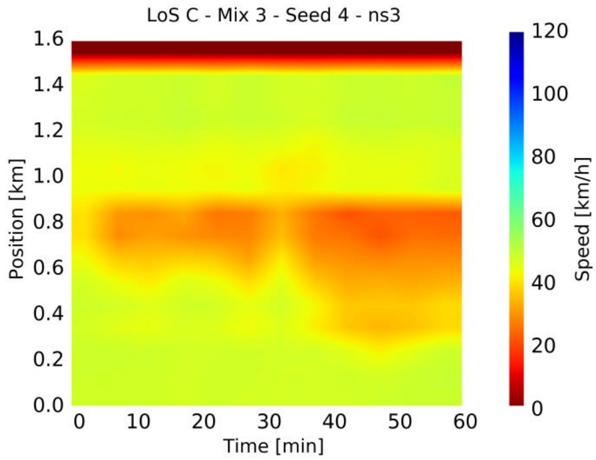
(d)

Figure 5: Network-wide simulation results for use case 1. Error bars show the standard deviation among ten replications over one hour simulation time for the corresponding parameter combination.

Figure 5 summarises the network-wide simulation results for this scenario. Note that we deliberately omitted the plots both for the number of TORs and MRMs since their result was zero for all parameter combinations and all replications. When comparing these results to the ones presented in D4.2 [2], where baseline and traffic management Service 1 without communication where evaluated, we can verify that throughput and CO_2 emission results for LightComm, i.e., the "ideal" communication, are comparable to traffic management Service 1 results without any communication. The total number of critical events, i.e. events with a TTC lower than 3 s, is (on average) significantly lower than in D4.2. This is, however, in line with the results in D4.2 since the percentage of ToCs was fixed to 25% in the traffic management Service 1 case without communication and the percentage is now effectively down to 0% since no TORs had to be issued. Most distinct for the number of critical events KPI, we observe high standard deviations in the case of LOS C, traffic mix 3. This has already been observed in simulations for D4.2 and can be attributed to aggressive LV behaviour in the form of left overtaking manoeuvres when the bus lane is congested with the early-lane-changing CAVs.



(a)



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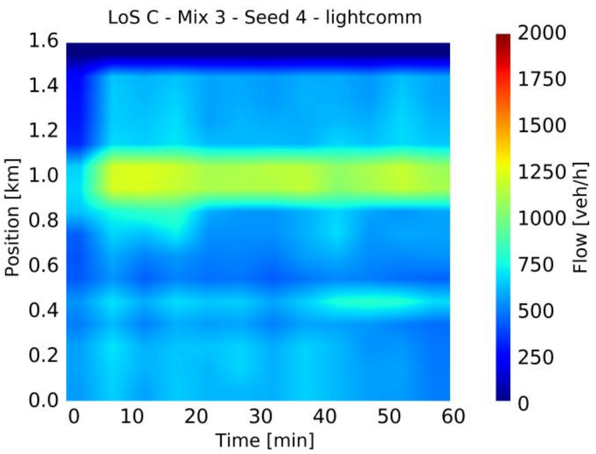

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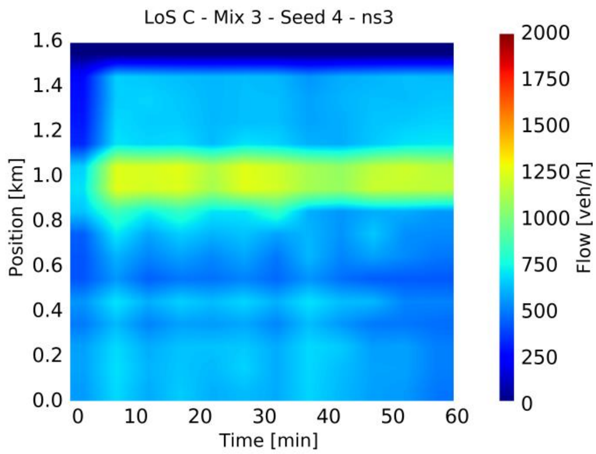


(d)

Figure 6: Example spatio-temporal plots visualising KPIs speed (a, b) and flow (c, d), respectively, for use case 1. For both KPIs, ideal (a, c) and realistic (b, d) communication results are shown side-to-side for easier comparison.

Apart from the verification of earlier results, we observe no significant differences between the results for ideal ("LightComm") and realistic ("ns-3") communication (cf. Figure 5). Even though some communication errors occur when ns-3 is used, no significant impact on the selected traffic KPIs can be observed for the parameter combinations considered in the performed simulation study (for details on communication KPIs, see the subsequent section). This suggests that the performance of the proposed traffic management algorithm is not significantly impaired by realistic communication. An inspection of local traffic efficiency KPIs speed and flow with spatio-temporal plots (an example is shown in Figure 6) supports this conclusion as no significant differences can be made out between the two communication modes.

Communication

This section analyses the impact of the traffic management measures in the performance of V2X communications. First, we analyse the congestion level of the V2X communications channel through the Channel Busy Ratio (CBR) metric. Table 3 shows the average CBR for all the vehicles in the simulation. The results are reported for all combinations of scenario parameters, i.e. levels of service (LOS A, B, and C) and traffic mixes (1, 2, 3). The obtained results show that for all the combinations of scenario parameters, the CBR is around or below 20 % (for the scenario with LOS C and traffic mix 3 that is characterised by the highest density of vehicles and highest connected vehicles share, respectively). This means that on average the V2X communications channel is only sensed as busy by the vehicles for 20 % of the time. Thus, the traffic management measures implemented for the TransAID Scenario 1.1 / Service 1 are not creating an excessive V2X communication load and vehicles can access the channel to transmit their messages.

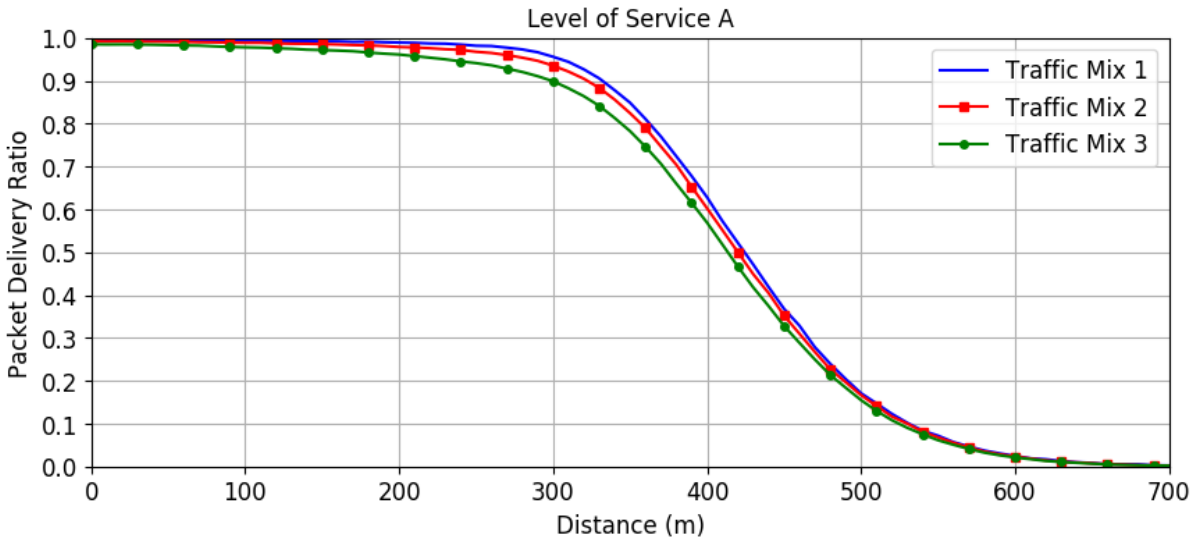
Table 3: Channel Busy Ratio for Service 1.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS A	2.03 %	4.17 %	7.39 %
LOS B	3.90 %	7.37 %	12.81 %
LOS C	6.07 %	11.40 %	22.94 %

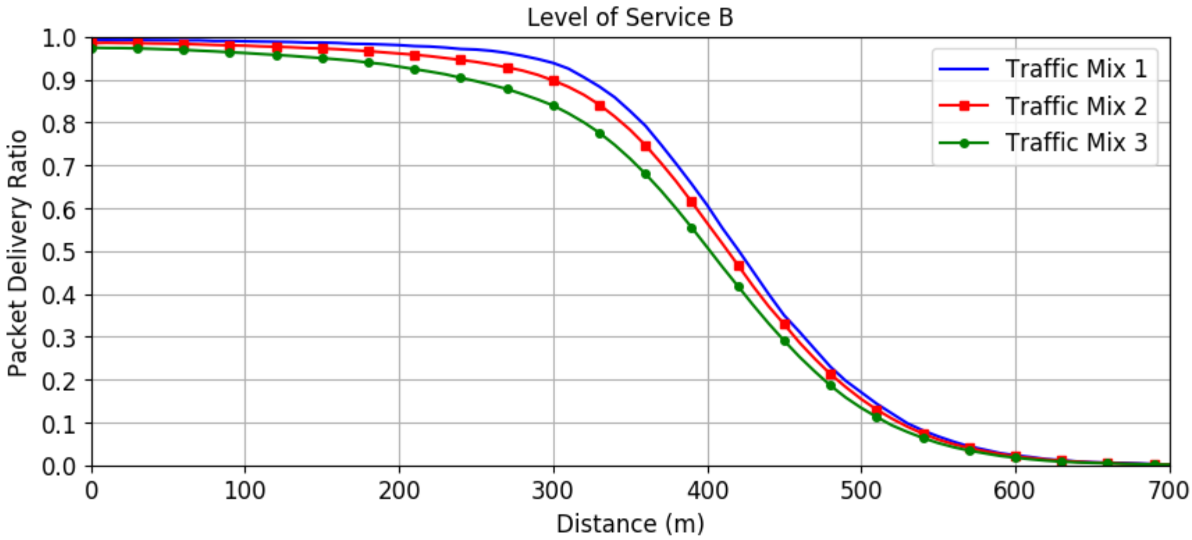
Table 4: Latency for Service 1.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS A	0.90 ms	0.94 ms	1.01 ms
LOS B	0.93 ms	1.01 ms	1.14 ms
LOS C	0.98 ms	1.10 ms	1.61 ms

Table 4 shows the average latency of the V2X communications performed during the simulations of Service 1. The latency measures the time elapsed between the transmission and reception of a packet at the application/facility layer. We can observe that the average latency measured for all combinations of scenario parameters is around 1 ms. These low latency values guarantee that the vehicles will receive the traffic management measures with enough time to safely execute the required manoeuvres.



(a)



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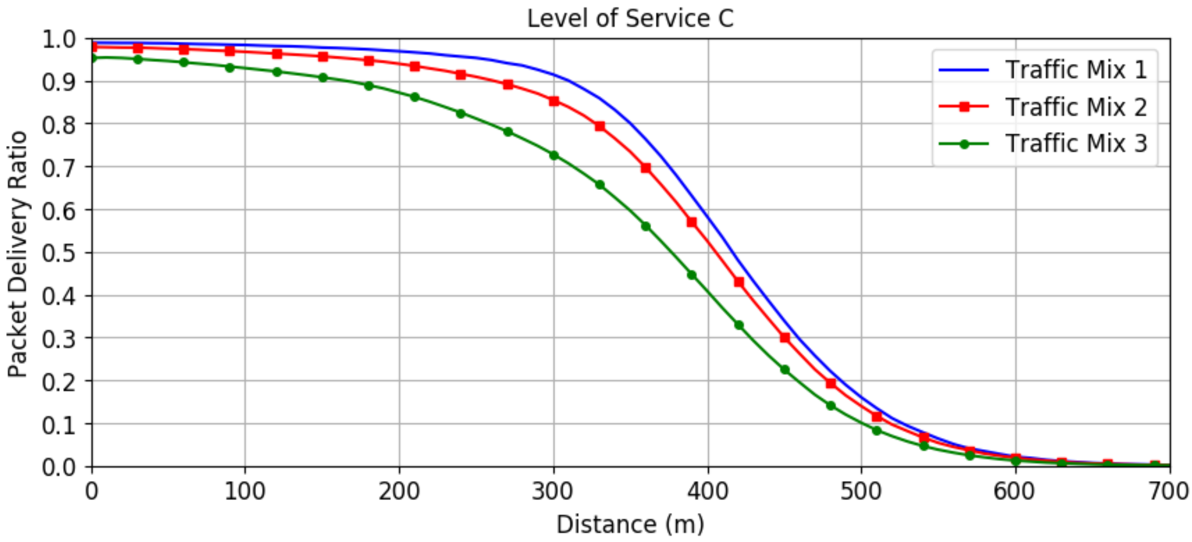


(c)

Figure 7: Packet Delivery Ratio of Service 1.

Finally, Figure 7 shows the PDR for the three different levels of service simulated in Service 1. The Packet Delivery Ratio (PDR) indicates the probability of successfully receiving a packet at a given distance. The reported PDR represents the average of all V2X transmissions occurring during the simulations. For each one of the levels of service, Figure 7 also includes the results obtained for traffic mixes in order to analyse the effects of increasing the number of CVs and CAVs in the scenario. As expected, increasing the number of vehicles with V2X capabilities results in a decrease of the PDR at the same distance due to the increased interferences and probability of packet collisions. Despite this PDR decrease with the increasing connected vehicles share in the scenario, the traffic results reported above show that the V2X communications do not negatively impact the traffic KPIs.

The overall analysis shows that the execution of the traffic management measures for the TransAID Scenario 1.1 / Service 1 does not negatively impact to the performance of the V2X communications.

3.1.3 Discussion

The simulation results obtained after implementing the scenario and TM measures within the iTETRIS framework have confirmed the results of Deliverable 4.2 [2]: traffic efficiency is not impaired by higher penetration rates of C(A)Vs (LOS A, B, and C), despite operating with increased headways. In addition, traffic safety improves even further since no TORs had to be issued and, hence, no MRMs had to be performed. Moreover, the comparison of simulations with (a) ideal and (b) realistic communication has shown no significant differences between the two, suggesting an unimpaired performance of the proposed traffic management measures.

The analysis conducted using the ns-3 simulator (i.e. realistic V2X communications) has shown that the traffic management measures of TransAID’s Service 1 do not negatively impact the performance of V2X communications. The average channel load sensed by the vehicles (i.e. CBR) is below 23% for all combinations of scenario parameters under study, which indicates that the implemented traffic management measures do not lead to high levels of V2X channel load. The analysis of the PDR shows that the increase in the number of connected vehicles increases the interferences causing a decrease of the PDR. This is the normal operation of V2X communications that get affected by, e.g., the increasing interference levels and hidden terminal problem. However, the overall analysis shows that the V2X communications can support the transmission and reception of the necessary messages for the execution of the TM measures for the simulated traffic demands.

Finally, we note that there are still lessons to be learned for several aspects of the scenario, which should be, especially with respect to the real-world prototype, kept in mind for future work:

a) **Road-side infrastructure**
   - RSU locations should be chosen deliberately with respect to communication radius, communication delay, and the traffic management algorithm.
   - The merge area should be chosen long enough for the timely reception of headway advice messages since CAM-based detection of vehicles on left lanes in the merge area leads to delays.

b) **Automated vehicle control**
   - CAVs currently change to the right-most (bus) lane as soon as the path info has been received which leads to congestion for high demands and penetration rates.

c) **RSU software**
   - A central traffic management logic (TMC) is assumed which controls the RSUs. Therefore, a direct/wired connection to the physical RSUs is desirable.
   - CAM state information of vehicles should be estimated by TMC in case of missing timely state information.

d) **V2X implementation**
   - The frequency of retransmission of the infrastructure advices should be further studied to guarantee the correct reception of the advices while keeping the channel load as low as possible to avoid negatively impacting the performance of V2X communications.

3.2 Scenario 2.1: Prevent ToC/MRM by providing speed, headway, and/or lane advice

3.2.1 Introduction

The cooperative merging system is an iterative, distributed intelligent control system that aims for safe and optimal vehicle manoeuvres of LVs, CVs, and (C)AVs. The scenario is shown in Figure 8.

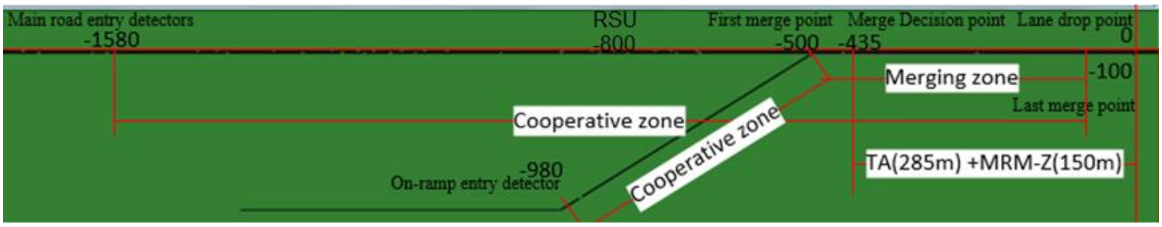


Figure 8: Motorway merging scenario.

The setup is described in more detail in [2], but most important is that vehicles can be influenced with speed advice by the merging assistant in the cooperative zone. This zone starts as soon as vehicles are detected by entry detectors (-1580 m on the mainline, -980 m on the on-ramp). Modelling of approaching vehicles also occurs in this zone. The merging area stretches from -500 m to 0 m, but for safety a guided merge should take place at -435 m, because at that moment a ToC and MRM can still take place.

The system has several measures it can take to improve traffic flow. In the following they will be referred to as follows:

a. ToC and MRM fail-safe
This strategy uses merging system to monitor only the merging area; issue ToC when there is no possible gap.
b. Merging guidance
This strategy issues speed advice of 60 km/h to 100 km/h for each on-ramp CAV/CV, issue ToC when there is no possible gap.
c. Lane advice on the mainline left lane
This strategy prohibits lane changing for vehicles on inner lane, therefore vehicles on the left lane are not allowed to perform a lane change to the right lane.
d. Cooperative speed advice for gap creation
This strategy gives speed advice for the mainline vehicles to create gaps for mergers.
e. Cooperative lane advice for gap creation
This strategy gives lane advice on the mainline vehicles to create gaps for mergers.
f. Intelligent ramp metering
This strategy will hold vehicles at the on-ramp when no suitable gap can be found, or when it would disturb mainline traffic too much.

While traffic management strategies (a) to (c) were implemented in the first iteration, strategies (d) to (f) are planned to be investigated during the second iteration. Figure 9 shows the message flow employed in the implementation of Service 2.1 in the first iteration of the project.

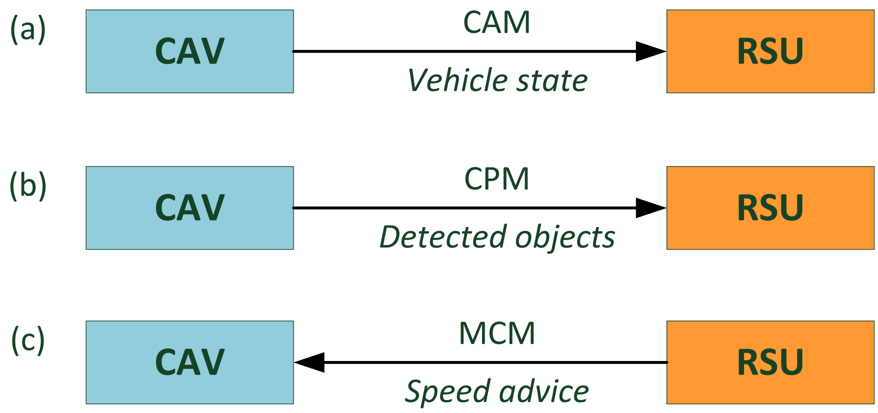


Figure 9: Communications in Scenario 2.1.

It is good to keep in mind that adding those strategies will increase the number of messages exchanged on the channel. This is not just more MCM for strategies (d) and (e), but the queue at the ramp meter will also increase the amount of CAM messages in the air. In the following we focus on the effect of communication related effects related to strategies (a) to (c). Table 5 lists the communication requirements of the different strategies and elements:

Table 5: Communication effects for motorway merging.

Component	Message	Direction	Effect of packet loss
Queue model	CAM, CPM	Vehicle - RSU	Skip model update from originating vehicle.
ToC fail-safe	MCM	RSU - Vehicle	MCM is repeated, response of vehicle will be delayed
Merging guidance	MCM	RSU - Vehicle	MCM is repeated, so the vehicle keeps following the previous MCM info if it exists.
Lane advice: Keep left	-	-	-

The last measure (c) is a static measure that holds for all vehicles and is implemented with a solid lane marking. Therefore, it is not affected by communication. The messages were designed in a way that missing one would not affect the performance too much. The speed advice is recalculated every second in case of unexpected changes in the underlying model. Therefore, missing one message basically means that there is still an old advice that is probably close to the optimal being followed.

The queue model is required for the strategy to have a good overview of all vehicles approaching the merging area both from the on-ramp and at the mainline. As explained in [14], the base model just extrapolates the previous measurement of the vehicle if no new data is coming in. For LVs this means that the entry loop detection is propagated, while for CVs the speed and position can be updated based on the latest CAM. If a CAM update is missing, it would simply use the previous CAM or even the entry detector data like for an LV.

For the simulations, all parameters are kept the same, except that a model is added for each message that is being transmitted. This model is based on the RSU being above the road 800 m before the end of the merging lane. This means that there is very few data from vehicles close to the entry detector (1580 m – 800 m = 780 m communication distance) and vehicles have the best communication capabilities during the critical area of the speed guidance 1300 m – 300 m until the end of the merging area. The merge decision point where the ToC would be issued is at 435 m, which is also inside communication range.

Simulation of the communication was not done using iTETRIS. For the sake of simplicity and portability of the algorithms to the planned field trials, the software was developed using Java. As applications for iCS are relying on the BaseApp module written in C++, using iTETRIS for this scenario was not feasible. To estimate the sensitivity to communication errors, we used Packet Error Rates (PER) as observed for other services. The PER curves used have been obtained through a detailed analytical model that models the packet errors produced by propagation effects and interferences for the IEEE 802.11p wireless technology. The PER curves here considered have been obtained for a transmission power of 23 dBm, a sensitivity threshold of -85 dBm, and considering packets that have 190 bytes and are transmitted using the 6 Mbps data rate. The Winner+ B1 model is used to model the radio propagation effects. Although the resulting simulation model was considered as a function depending only on the distance between communication pairs different PER curves have been obtained for each traffic mix and level of service, to account for the different overall interference levels, which depend on the different traffic density and penetration rate of the wireless technology. The PER tables had a resolution of 25 m and if in the simulation two nodes were not exactly spaced apart by a multiple of 25 m, interpolation between the two closest values was used.

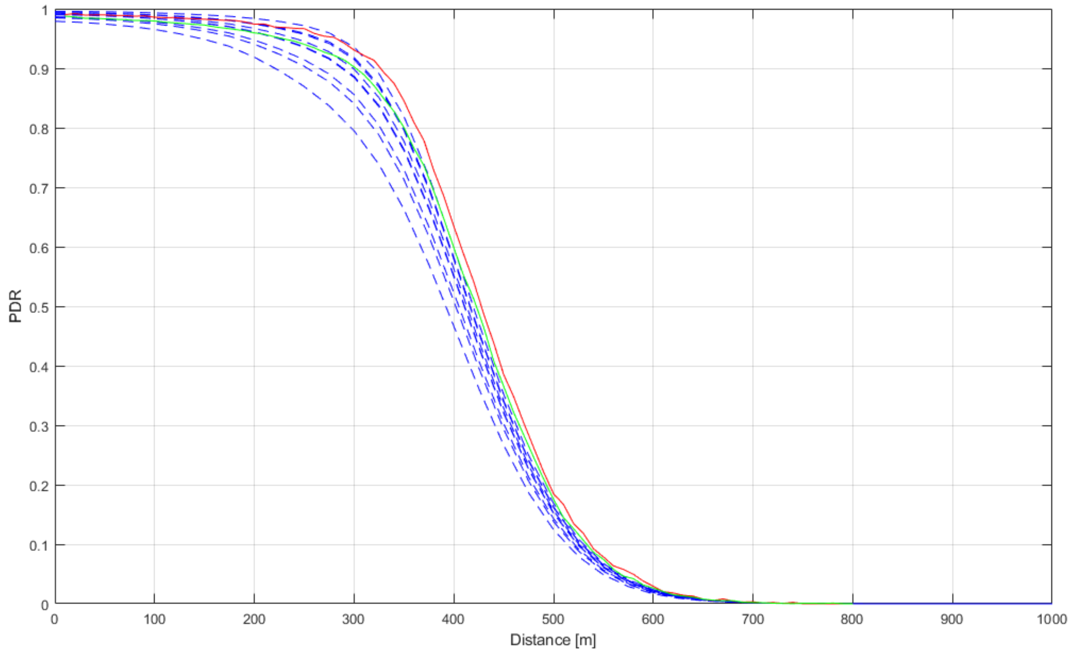


Figure 10: Packet Delivery Ratio (PDR) for different traffic mixes as a function of communication distance.

Figure 10 shows the Packet Delivery Ratio (PDR) for different traffic mixes (share of LV/CV/CAV according to [1]) and levels of service. The blue lines indicate the theoretical model used, while the green (LOS B, mix 1) and red (LOS A, mix 1) are obtained with iTETRIS simulation. Increasing the share of C(A)Vs and LOS results in poorer performance.

3.2.2 Results

Since this work focusses mostly on the effects of the communications, the entire work of WP4 is not repeated here. A test scenario with LOS C and fleet mix 2 communication parameters was used, as this could be considered the worst case situation. Both scenarios were executed for 10 simulation runs with as a main indicator of performance the average ToC rate. The standard deviation represents the deviation of the ToC values between different runs. Results are shown in the following table:

Scenario	**ToC average**	**ToC standard deviation**
No communication simulation	10.28	1.05
LOS C mix 2 communication	9.96	1.42

The packet error rate was 12.96 % on average with a standard deviation of 1.24 %. The ToC seems to have improved with increasing PER, but this is still well within one third of a standard deviation. This means the single tailed Student-T test has a P value equal to 0.71 (generally 0.95 is considered significant). Therefore, the conclusion is that the performance of the service did not change significantly by adding a communication model.

3.2.3 Discussion

The robustness of the communication protocols ensured that missing 12.96 % of the messages on average did not result in a significant change of performance. The planning of the RSU location greatly assisted in this keeping optimal coverage in the area where it is really important.

3.3 Scenario 3.1: Apply traffic separation before motorway merging/diverging

3.3.1 Introduction

The goal of service 3 is to separate AVs from non-AVs in different lanes upstream of the merge area of two motorways. Thus, complex vehicle interactions due to merging operations in mixed traffic conditions that could eventually lead to numerous ToCs/MRMs can be avoided. The simulation analysis conducted in the context of [2], that excluded communications, demonstrated conflicting results in terms of traffic efficiency and safety. Although throughput was marginally increased, average network speed and safety were noticeably decreased. Within the scope of this document, the proposed traffic separation policy is evaluated in the presence of realistic communication protocols to identify the potential impacts of communication errors on its performance.

In the case of ideal communications, perfect information regarding vehicle state is assumed and the communication range of RSU is considered infinite. However, in real-world conditions, communication errors may exist due to latency or package loss, and the communication range of RSU is finite. Hence, the length of the traffic management area and the road environment play an important role regarding the required number of RSUs and their placement on the road network to ensure coverage and efficacy of the traffic management plan. Since the traffic management area extends to approximately 3000 m for Scenario 3.1 and typical RSU communication range spans to 500 m, we select an equidistant placement of three RSUs along the traffic management area. Their exact locations are given in Table 6 and shown in Figure 11.

Table 6: Location of RSUs in Scenario 3.1.

RSU ID	Distance from end of Merge Area
“RSU 0”	500 m
“RSU 1”	1500 m
“RSU 2”	2500 m

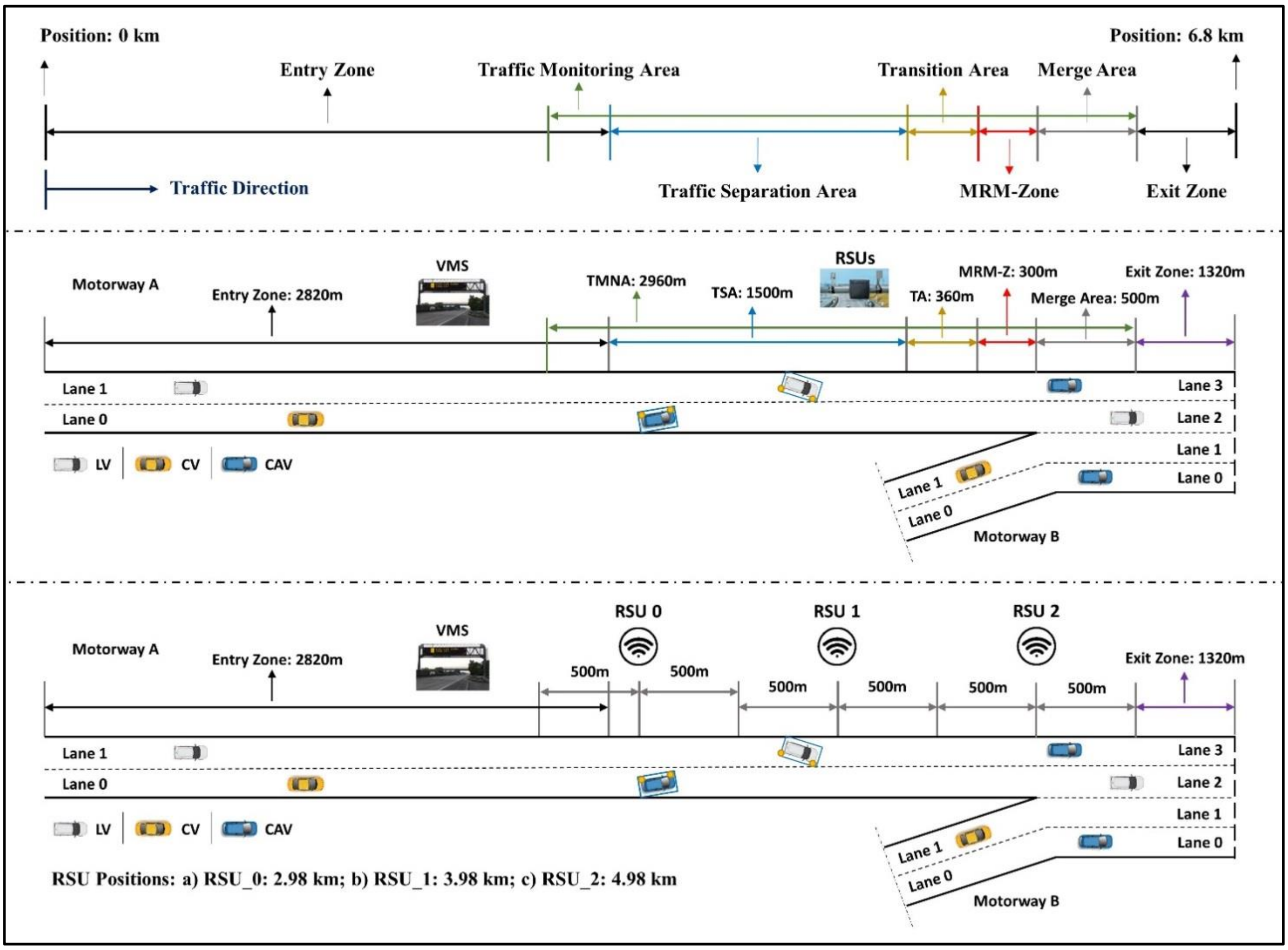


Figure 11: Schematic representation of Scenario 3.1.

The essential part of the communication protocol for Service 3 involves the exchange of three types of messages between the RSU and the CAV. Two types are transmitted by the RSUs and one by the CAVs (see Figure 12):

- An MCM containing lane change and TOR advice,
- an IVIM containing speed limit information, and
- CAMs containing the current vehicle state.

In contrast to the case of no-communications (perfect knowledge regarding every vehicle state) that was considered for the development of the traffic management plans in [2], the traffic management logic now counts on information pertaining to the CAV's state (position, speed, acceleration, automation mode, etc.) collected via CAM messages transmitted on regular intervals by the CAVs. Received CAMs are centrally processed by the RSU (wired to the TMC) using the same traffic management program.

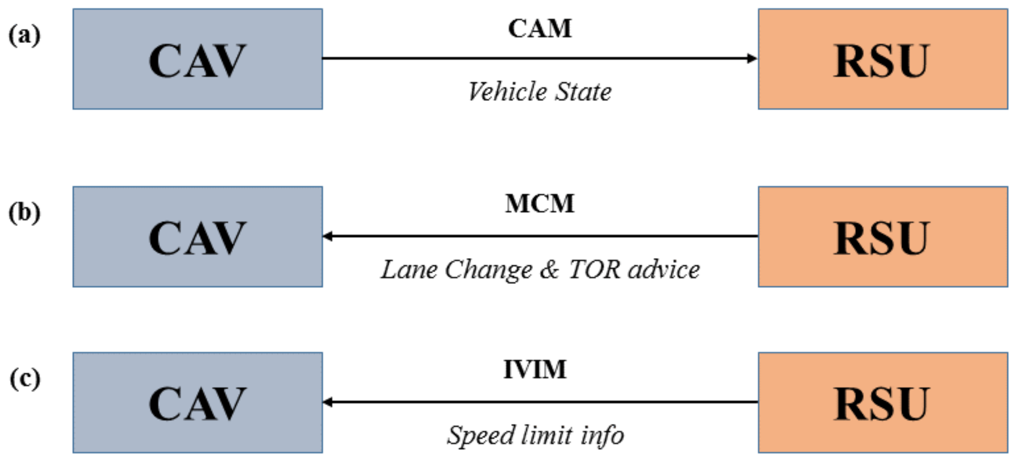


Figure 12: Communications in Scenario 3.3.

The RSU is informed about the exact location (per lane) of the CAVs approaching the traffic separation area via the CAM messages. When a CAV drives on the non-CAV-designated lane upon entrance to the traffic separation area, the RSU sends a MCM message to instruct a lane change to the CAV towards the CAV-designated lane. The same MCM message includes a TOR advice for those CAVs that will not accomplish the lane change manoeuver within the traffic separation area due to surrounding blocking traffic. Eventually, in the case of an MRM in the proximity of the merge area, the RSU broadcasts IVIM messages to CAVs to inform them about the reduction of the speed limit for safety reasons. For more information on the protocol, see also [9].

3.3.2 Results

In the following, we solely present simulation results (traffic KPIs) for the case of ideal communications (i.e. LightComm). Simulations pertaining to the case of realistic communications (i.e. ns-3) are quite computationally intensive and could, due to additional technical hindrances, not be completed by the time of submission of this version of the Deliverable. Due to significantly increased traffic demand compared to the other scenarios, Scenario 3.1 requires substantially higher computational effort to simulate V2X communications. The exact requirements in computational time regarding each parameter combination examined in Scenario 3.1 when using ns-3 are listed in Table 7. It can be observed that computational effort increases exponentially towards higher traffic demand levels. Note that the time required to simulate one second of simulation time depends on the simulation scenario at this specific time (i.e. number of vehicles in the simulation, number of transmitted messages etc.). Thus, a linear estimation of how long the simulations will last, taking into account the time spend to simulate X seconds, is not reliable. Usually, it takes much more time to simulate a second once the simulation has advanced sufficiently (i.e. second 3000) than at the beginning of the simulation. However, the simulation results for the case of realistic V2X communication will be integrated in a future version of this Deliverable.

Table 7: Computational requirements of the simulations of Service 3 using the ns-3 simulator.

	Level of Service A			Level of Service B			Level of Service C		
	Simulated sec.	**Comp. Time**	**RAM**	**Simulated sec.**	**Comp. Time**	**RAM**	**Simulated sec.**	**Comp. Time**	**RAM**
Traffic mix 1	5000	58.4 h	12.2GB	3396	244	24.4GB	2156	244	39.0GB
Traffic mix 2	5000	75.8 h	14.0GB	3338	244	26.8GB	2536	244	26.8GB
Traffic mix 3	5000	117.8 h	17.6GB	3293	244	26.8GB	3373	244	29.3GB

Table 8 shows the time required to simulate the different parameter combinations employing the LightComm module to simulate ideal communications. It can be appreciated the significant reduction of computational time obtained thanks to the use of the new module in comparison with the use of the ns-3 simulator.

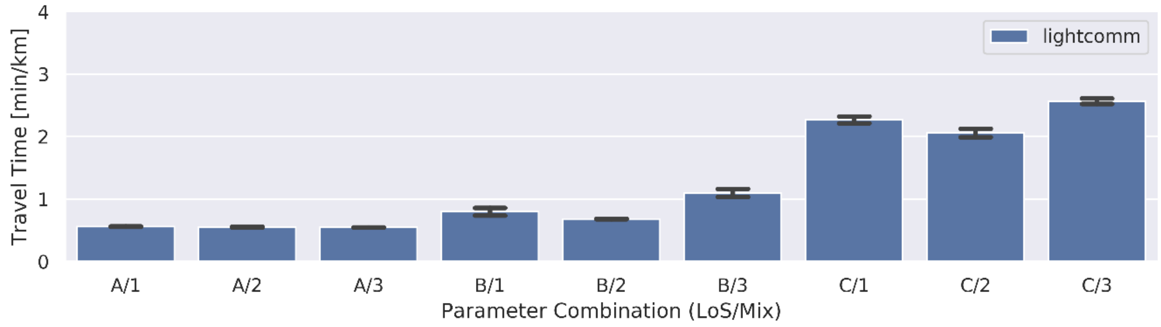
Table 8: Computational requirements of the simulations of Service 3 using the LightComm simulator.

	Level of Service A		Level of Service B		Level of Service C	
	Simulated sec.	**Comp. Time**	**Simulated sec.**	**Comp. Time**	**Simulated sec.**	**Comp. Time**
Traffic mix 1	5000	11.85 h	5000	32.67 h	5000	89.20 h
Traffic mix 2	5000	21.41 h	5000	50.00 h	5000	68.30 h
Traffic mix 3	5000	39.47 h	5000	54.57 h	5000	74.83 h

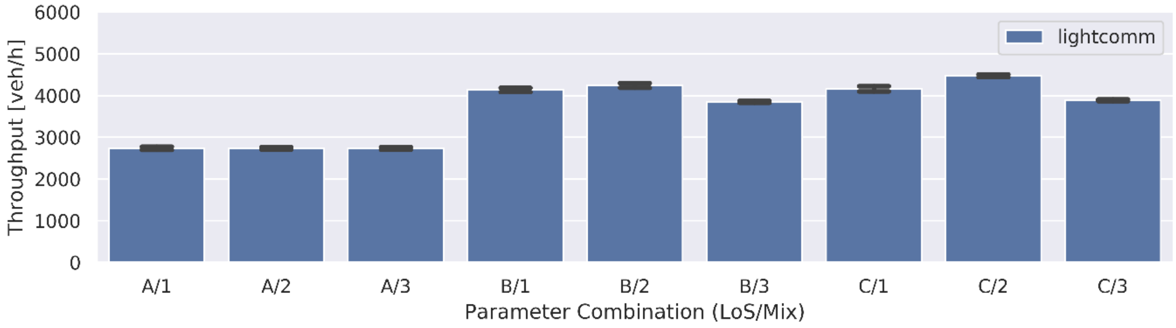
Traffic

Traffic efficiency is assessed based on average network statistics (travel time and throughput bar plots) and spatio-temporal diagrams of speed and flow (obtained from simulated detector raw output). On the contrary, traffic safety and environmental impacts are assessed explicitly based on network-wide statistics (safety-critical events and CO_2 emissions bar plots).

Figure 13 depicts average network statistics regarding traffic efficiency, traffic safety, and environmental impacts for the LightComm case. These statistics are compared with the relevant simulation results in [2], to identify differences between ideal communications (iTETRIS simulations) and no communications (SUMO simulations). Throughput is similar between the aforementioned cases. However, we can observe differences between the other statistical categories which are more significant for mean values of travel time and safety-critical events. The reason for the observed differences can be attributed to the fact that safety-critical events are reduced for the iTETRIS simulations as a result of improvements in the car-following model of automated vehicles. Nonetheless, note that these differences concern specific parameter combinations and that general trends in variation of traffic KPIs across the full spectrum of parameter combinations comply with those reported in [2]. Similar findings are supported by the spatio-temporal contour plots that display changes in local traffic conditions (see Figure 14).



(a)



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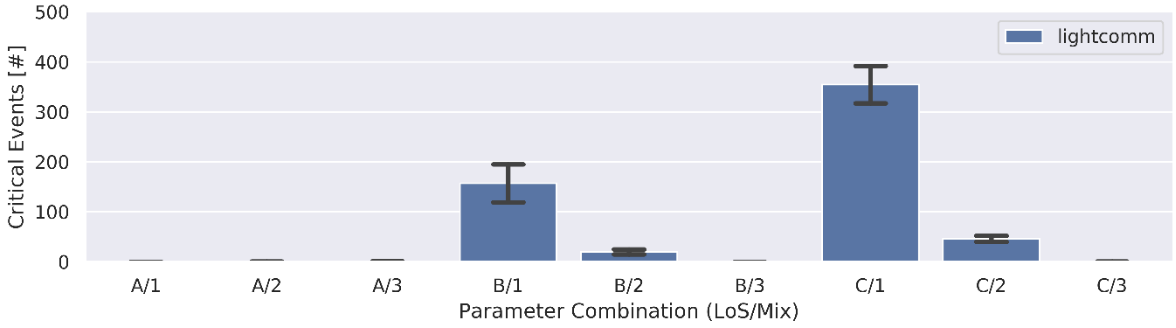

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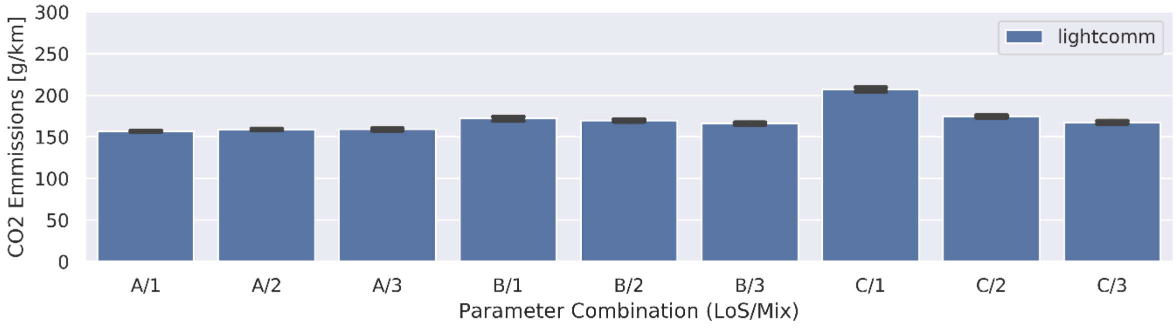
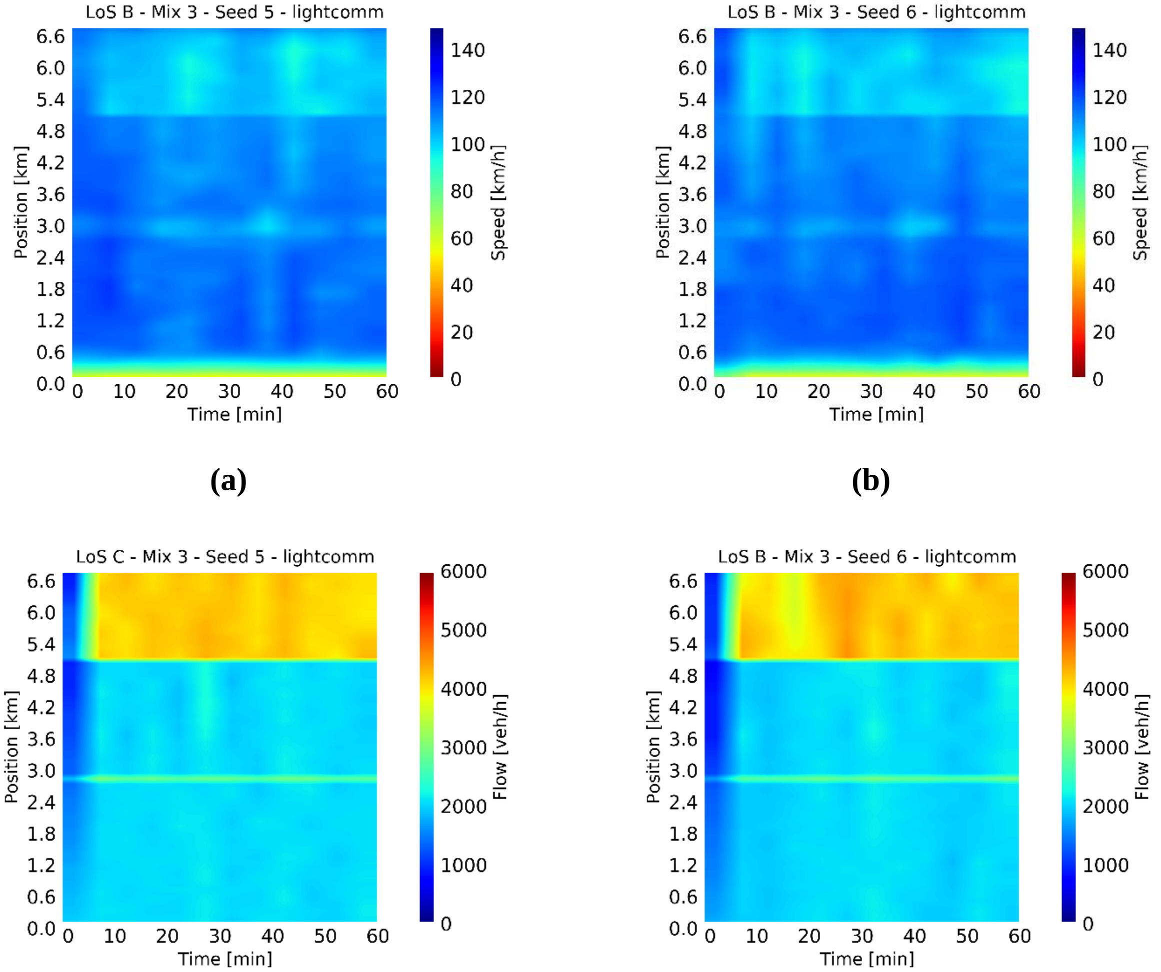


(d)

Figure 13: Simulation results (average network statistics) for Scenario 3.1. Error bars show the standard deviation among ten replications over one hour simulation time for the corresponding parameter combination.



(a) (b) (c) (d)

Figure 14: Example spatio-temporal diagrams for measured speeds (upper row) and flows (bottom row) for Scenario 3.1. Both columns correspond to ideal communications.

3.3.3 Discussion

As aforementioned in more detail, simulation results considering realistic V2X communication protocols could not be included in the present version of this document. Thus, no conclusions can be drawn based on the latter analysis with respect to the impacts of realistic V2X communications on the performance of the traffic separation strategy. An updated analysis will be provided in a future version of this document that considers realistic communication protocols.

3.4 Scenario 4.2: Safe spot in lane of blockage

3.4.1 Introduction

The objective of the traffic management plan developed in the context of this scenario is to guide CAVs to safe spots upstream of existing road works when drivers fail to take over vehicle control after system-initiated take-over requests. Simulation results presented in [2] demonstrated the traffic and safety benefits of preventing CAVs from stopping on the open lane near the work zone while providing the necessary information for reaching pre-specified safe spots upstream of the work zone. However, communications were not considered in the latter simulation experiments.

Here we examine the performance of our devised traffic management plans in the presence of ideal and realistic communications. Since the communication range of RSUs is finite in the real world, it is essential to properly determine the required number of RSUs and their corresponding locations on the road network to ensure coverage and, therefore, the efficiency of the proposed traffic management plan. Assuming that typical RSU range is approximately 500 m, the placement of a single RSU 500 m upstream of the work zone meets the communication and coverage requirements of this scenario (see Figure 15) for both the urban and motorway scenarios. Hence, the infrastructure will be able to promptly warn the approaching CAVs about the presence of the construction site, and guide them to the safe spot if MRM is initiated on the open lane.

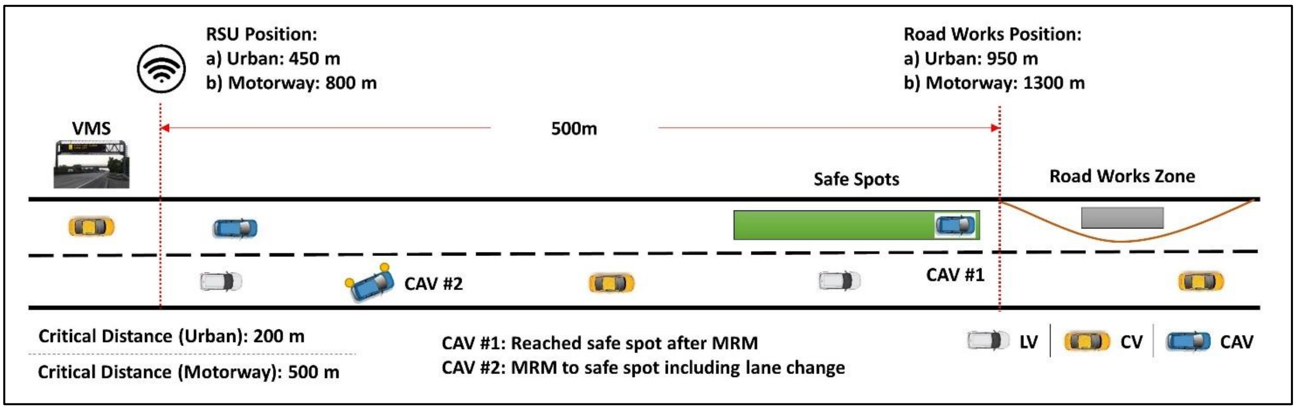


Figure 15: Schematic representation of Scenario 4.

The essential part of the communication protocol for service 4 involves four types of messages exchanged between the RSU and the CAV. Three types are transmitted by the RSUs and one by the CAVs (see Figure 16):

- a DENM containing the road works info,
- an MCM containing MRM advice,
- a MAPEM containing the safe spot location, and
- CAMs containing the current vehicle state.

In contrast to the case of no-communications that was considered for the development of the traffic management plans in [2], the traffic management logic now counts on information pertaining to a CAV’s state (position, speed, acceleration, automation mode, etc.) collected via CAM messages transmitted on regular intervals by the CAVs. Received CAMs are centrally processed by the RSU (wired to the TMC) using the same traffic management program.

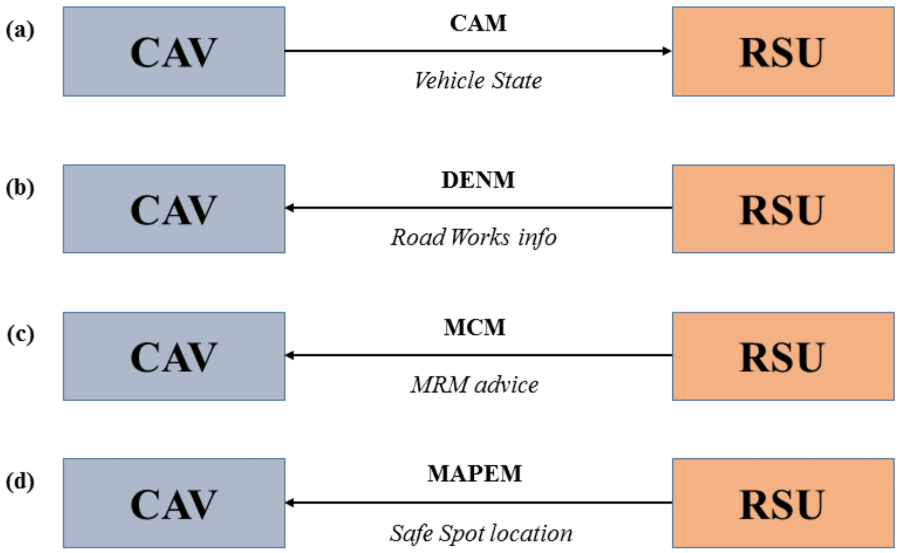


Figure 16: Communications in Scenario 4.

The RSU periodically broadcasts DENM messages informing the CAVs entering the communication range of the RSU about the upcoming road works. Moreover, the RSU monitors the state of CAVs and specifically their driving mode and available lead-time in case of take-over requests. When a take-over request is issued, the RSU oversees the automation status of the CAV and if it does not shift to manual within a pre-specified time interval (determined in [2]), it broadcasts MCM and MAPEM messages containing MRM advice and safe spot locations, respectively. Thus, CAVs can be guided to a safe spot upstream of the work zone as safely as possible without adversely affecting surrounding traffic. For more information on the protocol, see also [9].

3.4.2 Results

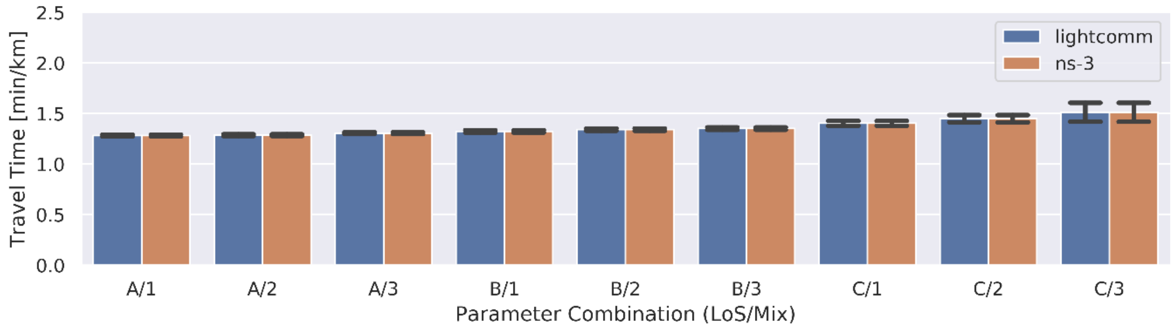
In the following, we present the simulation results (traffic and communication KPIs) obtained for this scenario (urban and motorway traffic conditions). The main goal of the assessment is to determine the robustness of the traffic management procedures with respect to the inclusion of realistic communication processes. Thus, we simulated all combinations of scenario parameters (demand level and vehicle mix) for ideal and realistic communications as described in Section 2.2.

Traffic

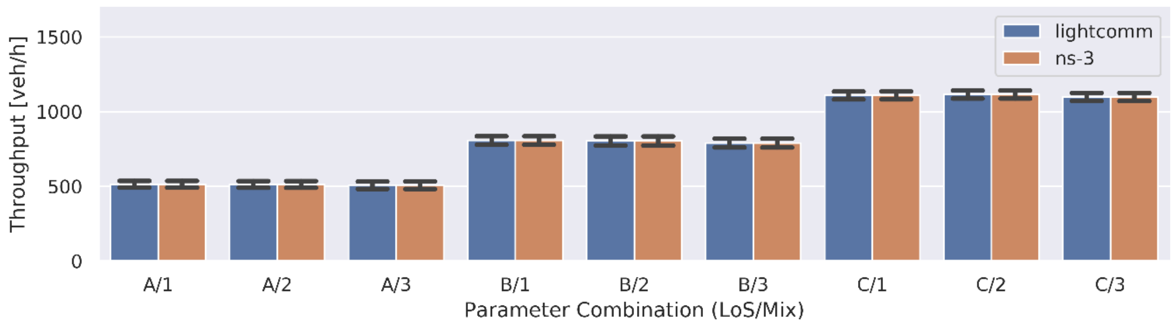
Traffic efficiency is assessed based on average network statistics (travel time and throughput bar plots) and spatio-temporal diagrams of speed and flow (obtained from simulated detector raw output). On the contrary, traffic safety and environmental impacts are assessed explicitly based on network-wide statistics (safety-critical events and CO_2 emissions bar plots).

Figure 17 depicts average network statistics for urban traffic conditions. Mean values and standard deviation between ideal (i.e. LightComm) and realistic (i.e. ns-3) communications are similar for each statistic category and parameter combination except for traffic safety metrics. Due to improvements in the car-following logic of automated vehicles, the mean values for safety-critical events are lower, but the previously observed trends across the examined parameter combinations are maintained. Thus, the simulation of realistic communication protocols did not adversely impact the efficacy of the simulated traffic management strategy. Every CAV that was foreseen to initiate an MRM was successfully guided to the safe spot and did not block the open lane next to the work zone.

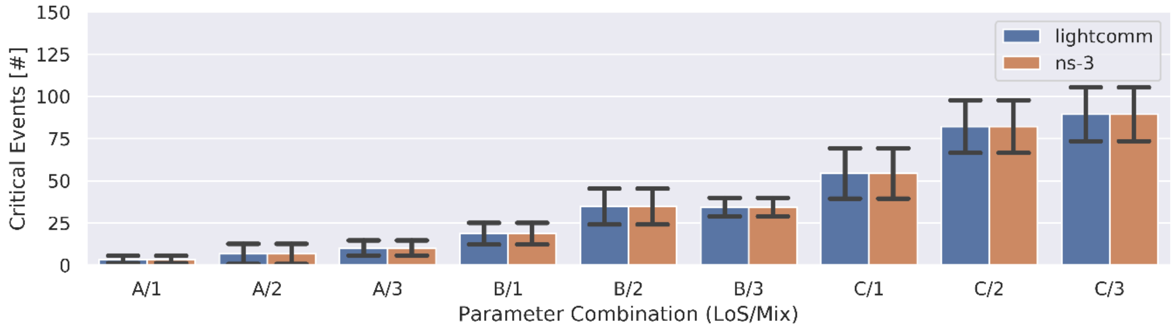
Similar observations are made when considering local network statistics. The traffic patterns observed in the spatio-temporal plots of speed and flow perfectly match between the LightComm and ns-3 cases irrespective of the examined parameter combination and simulation seed (cf. Figure 18). This supports the claim that the V2X communications do not impact the efficiency of the traffic management procedures for this scenario in urban traffic conditions. Moreover, it is noted that the simulation results related to the urban scenario and presented in Figure 17 and Figure 18 are similar to those included in [2] where V2X communications were not considered in the simulation experiments.



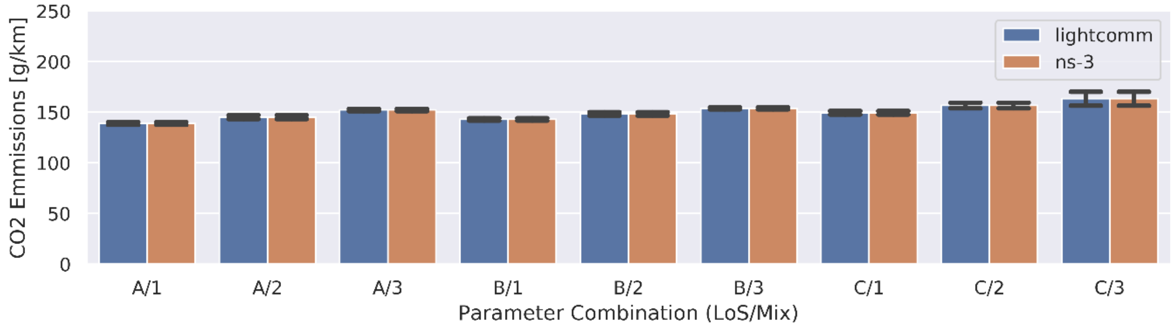
(a)



(b)



(c)



(d)

Figure 17: Simulation results (average network statistics) for Scenario 4.2 (urban network). Error bars show the standard deviation among ten replications over one hour simulation time for the corresponding parameter combination.

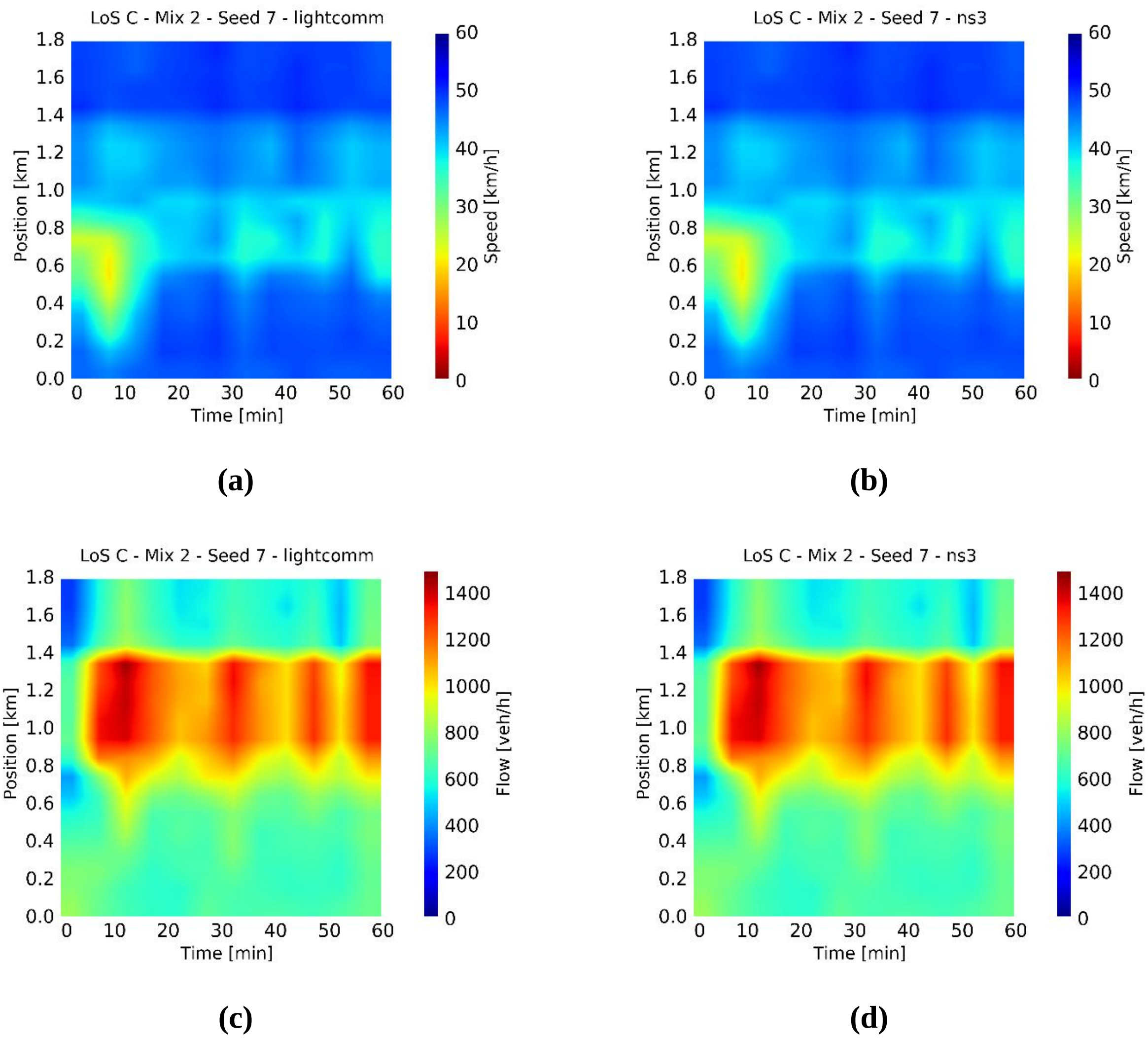
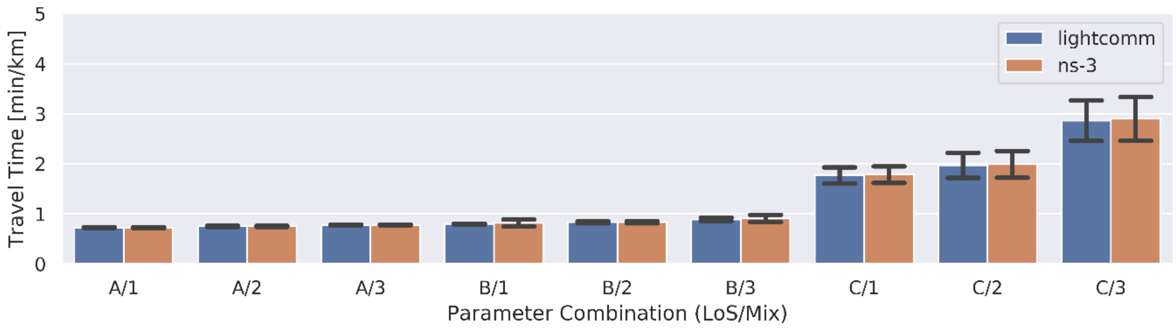


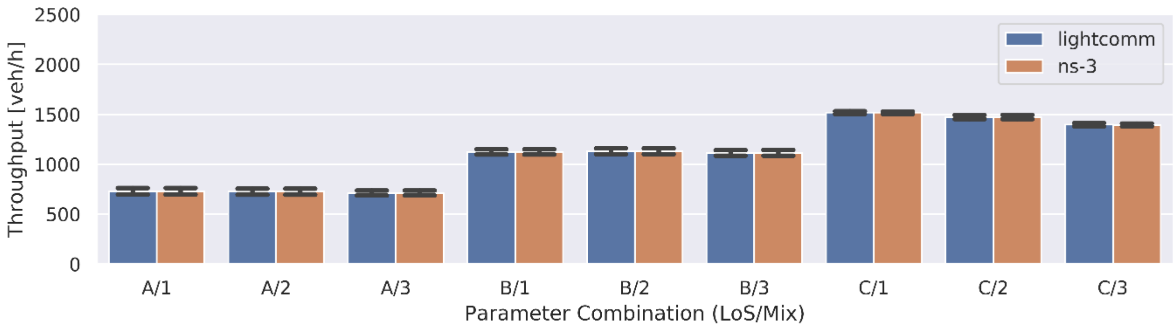
Figure 18: Example spatio-temporal diagrams for measured speeds (upper row) and flows (bottom row) for Scenario 4.2 (urban network, LOS C, vehicle mix 2, seed 7). The left column corresponds to ideal communications and the right column to realistic communications.

On the other hand, there are observable differences with respect to average network statistics between the LightComm and ns-3 cases for specific parameter combinations when motorway traffic conditions are examined. In particular, it is shown that mean values and especially standard deviations differ for parameter combinations LOS B/Mix 1 and LOS B/Mix 3 (see Figure 19). The differences are observable for travel time, safety-critical events, and CO_2 emissions since hourly throughput is unaffected due to uncongested traffic conditions on the motorway network for LOS B. Hence, it is apparent that realistic communications can impact traffic operations in the motorway scenario. These impacts can be ascribed to the unsuccessful guidance of CAVs to the safe spots due to communication errors.

Specifically, local network statistics (spatio-temporal diagrams of speed and flow) indicate that CAVs failed to reach the safe spot for individual simulation replications (seeds). For example, it can be seen in Figure 20 that for parameter combination LOS B/Mix 1 and seed 4 a CAV executed an MRM on the open lane thus causing shockwave (right top diagram) and forcing approaching vehicles to come to a full stop upstream of the work zone (right bottom diagram). Similar observations can be made for parameter combination LOS B/Mix 3 and seed 5 (see Figure 21). Other than the latter parameter combinations, communication errors did not undermine the performance of the traffic management strategy. The presented simulation results coincide with the ones presented in [2] where communications were not considered in the simulation experiments (except for traffic safety metrics as aforementioned).



(a)



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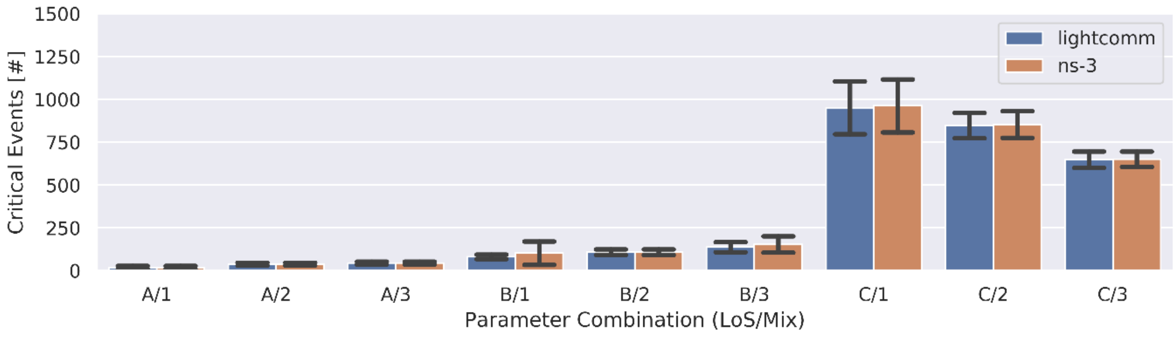
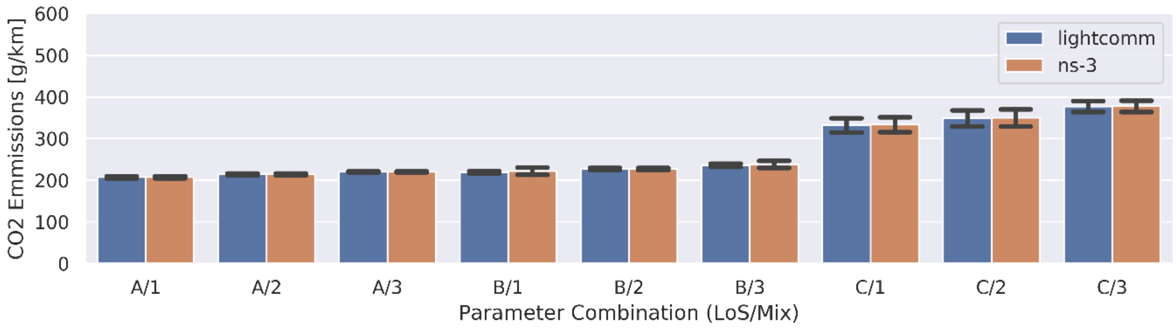
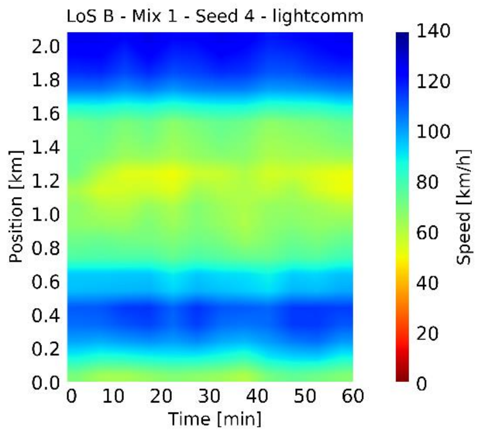


(c)

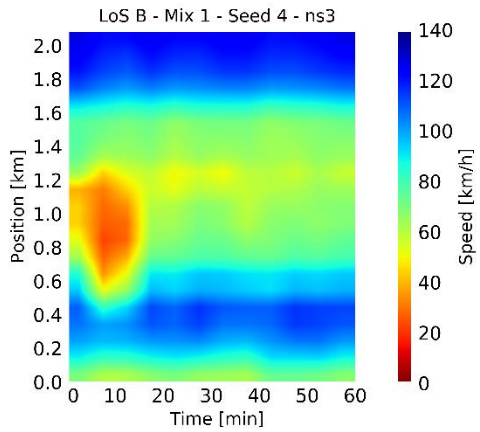


(d)

Figure 19: Simulation results (average network statistics) for Scenario 4.2 (motorway network). Error bars show the standard deviation among ten replications over one hour simulation time for the corresponding parameter combination.



(a)



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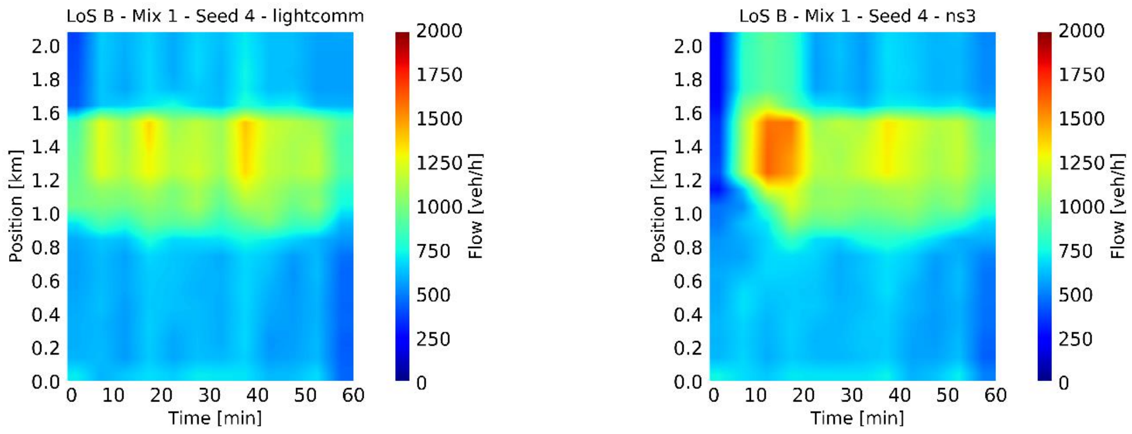
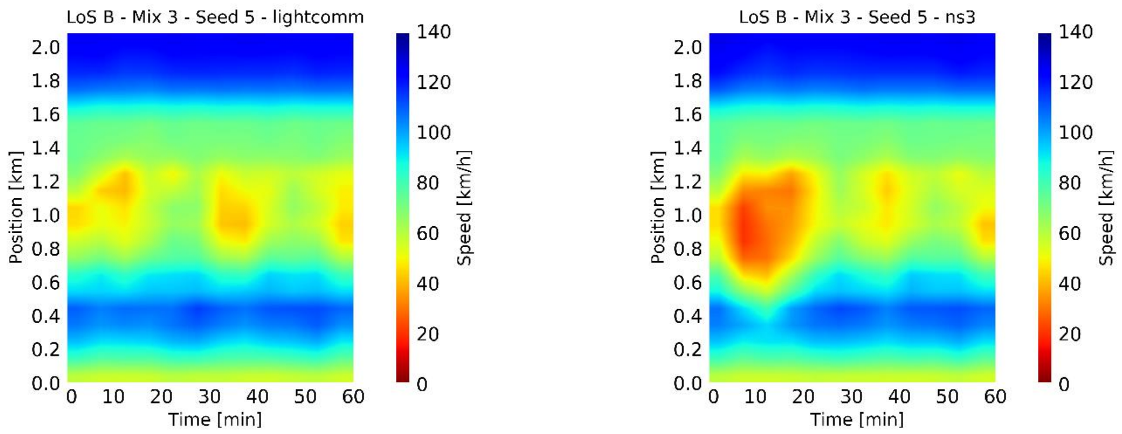
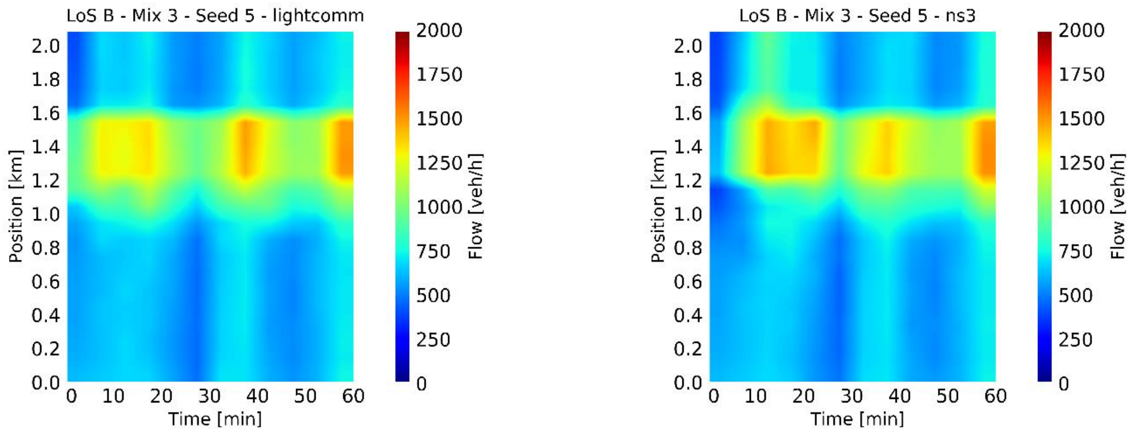


(c) **(d)**

Figure 20: Example spatio-temporal diagrams for measured speeds (upper row) and flows (bottom row) for Scenario 4.2 (motorway network, LOS B, vehicle mix 1, seed 4). The left column corresponds to ideal communications and the right column to realistic communications.



(a) **(b)**



(c) **(d)**

Figure 21: Example spatio-temporal diagrams for measured speeds (upper row) and flows (bottom row) for Scenario 4.2 (motorway network, LOS B, vehicle mix 3, seed 5). The left column corresponds to ideal communications and the right column to realistic communications.

Communication

This section evaluates the impact of the traffic management measures of Service 4.2 in the performance of V2X communications for the urban and motorway scenarios. First, we analyse the Channel Busy Ratio (CBR), which is a measure of the channel load defined as the percentage of time that the channel is sensed as busy. The results reported in this section show the average of the CBR measured by all the vehicles in the scenario. Table 9 summarises the CBR for the different levels of service (LOS) and traffic mixes evaluated in the urban scenario of Service 4.2. The reported results show that the CBR is below 20 % for all the considered parameters (i.e. traffic mix and LOS combinations). Actually, in most of these scenarios the CBR is below 10 %. This indicates that traffic management measures designed in Service 4.2 are not generating an excessive V2X communications load that could congest the communications channel in the urban scenario.

Table 9: Channel Busy Ratio for Service 4.2 in urban scenario.

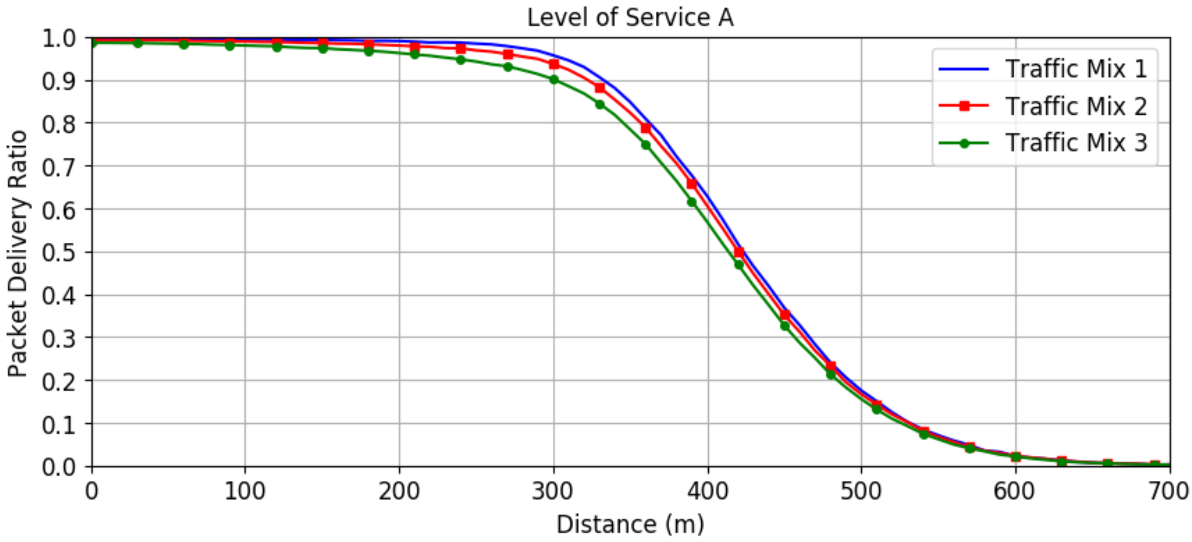
	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS A	2.26 %	4.16 %	7.30 %
LOS B	3.92 %	7.20 %	12.10 %
LOS C	5.96 %	10.86 %	18.43 %

Table 10: Latency for Service 4.2 in urban scenario.

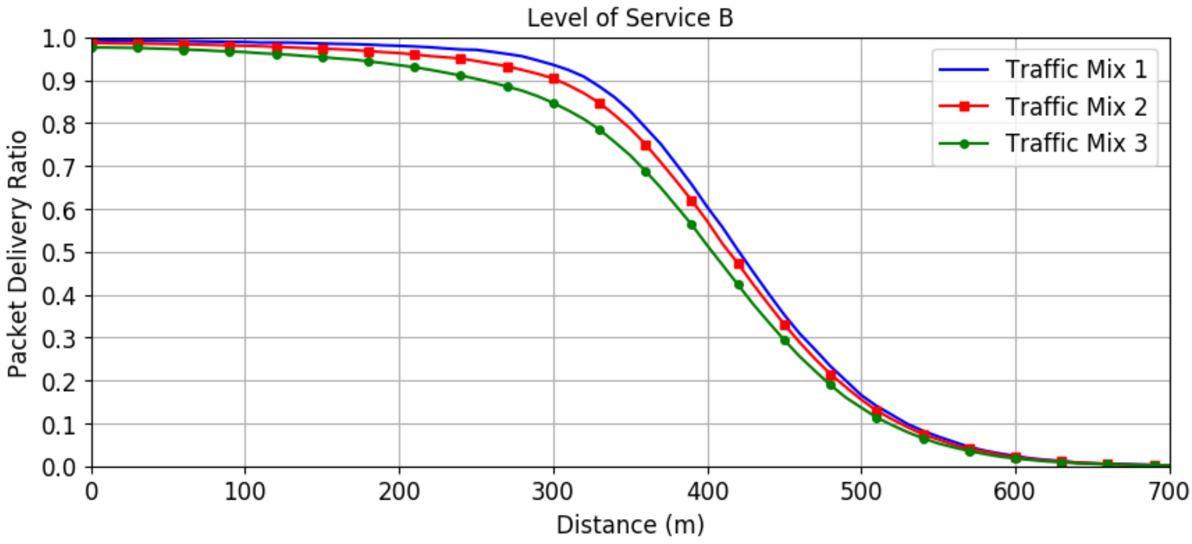
	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS A	0.95 ms	0.98 ms	1.04 ms
LOS B	0.98 ms	1.04 ms	1.15 ms
LOS C	1.01 ms	1.12 ms	1.38 ms

Table 10 shows the average latency measured in the urban scenario of Service 4.2 for all the different levels of service and traffic mixes. The latency is defined as the time elapsed between the transmission and the reception of a message at the application (i.e. that would represent the facilities layer in the ITS architecture) layer. Note that the ETSI standard for V2X messages like CAM or CPM does not retransmit a message again if the transmission failed. Thus, the latency metric computed here only takes into account successfully received messages. We can observe from Table

10 that the average measured latency is around 1ms for all the combinations of traffic mix and LOS. This time suffices for the successful implementation of the traffic management measures defined in Service 4.2.



(a)



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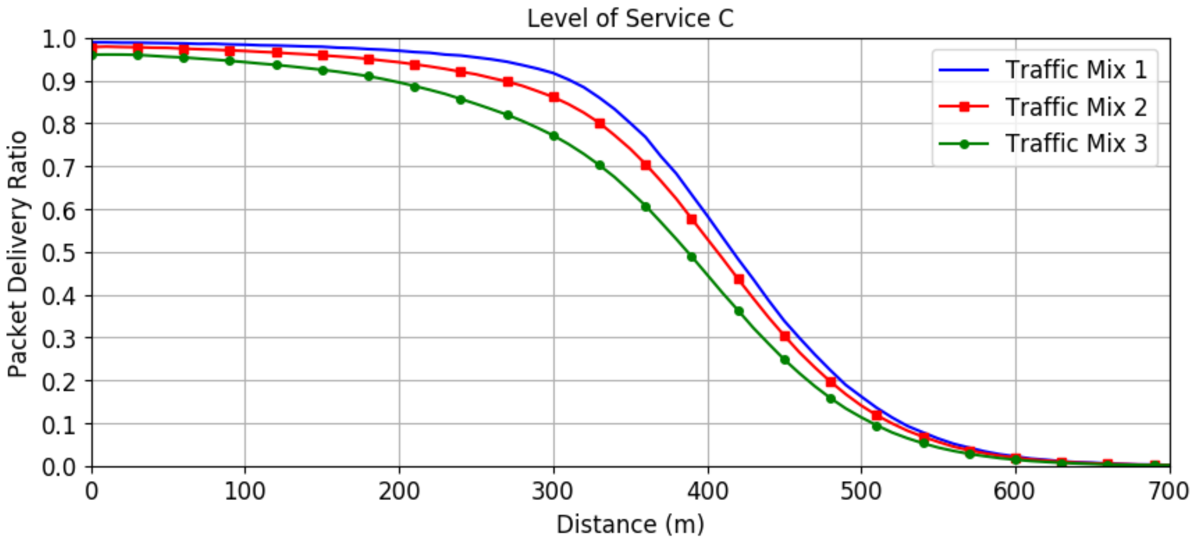


(c)

Figure 22: Packet Delivery Ratio for service 4.2 in urban scenario.

Figure 22 shows the Packet Delivery Ratio (PDR) of the different levels of services and traffic mixes evaluated in the urban scenario of Service 4.2. The PDR shows the probability of successfully receiving a message at a given distance between the transmitter and the receiver. The results reported in Figure 22 show that PDR decreases with the increasing number of vehicles (i.e. LOS and traffic mix combination resulting in a higher number of connected vehicles). This is the case because the more connected vehicles in the scenario, the higher the number of transmitted packets/messages. This results in more congested channel (i.e. more interference) and it is more likely that packet collisions occur.

The overall analysis of the communications KPIs for the urban scenarios under realistic conditions shows that the execution of the traffic management measures of Service 4.2 does not negatively impact the performance of the communications.

The obtained results show similar trends in the performance of the V2X communications for the motorway scenario than for the urban scenario. Table 11 summarises the CBR for the different levels of service and traffic mixes evaluated in the motorway scenario of Service 4.2. Most of the parameters configuration show that the average measured CBR is around 20 % or lower. These CBR levels indicate that during the simulations the V2X communication channel did not reached a high load level. As expected, the CBR increases with the level of service and traffic mix. Consequently, Table 11 shows the highest CBR levels for the LOS C with traffic mix 3 configuration. In this specific case, the CBR is 34.45 % which is much higher than the CBR measured for LOS A and traffic mix 0 (2.99 %). Anyway, for all the evaluated configuration parameters the measured CBR levels show that the designed traffic management measures are not causing an excessive V2X communication load.

Table 11: Channel Busy Ratio for Service 4.2 in motorway scenario.

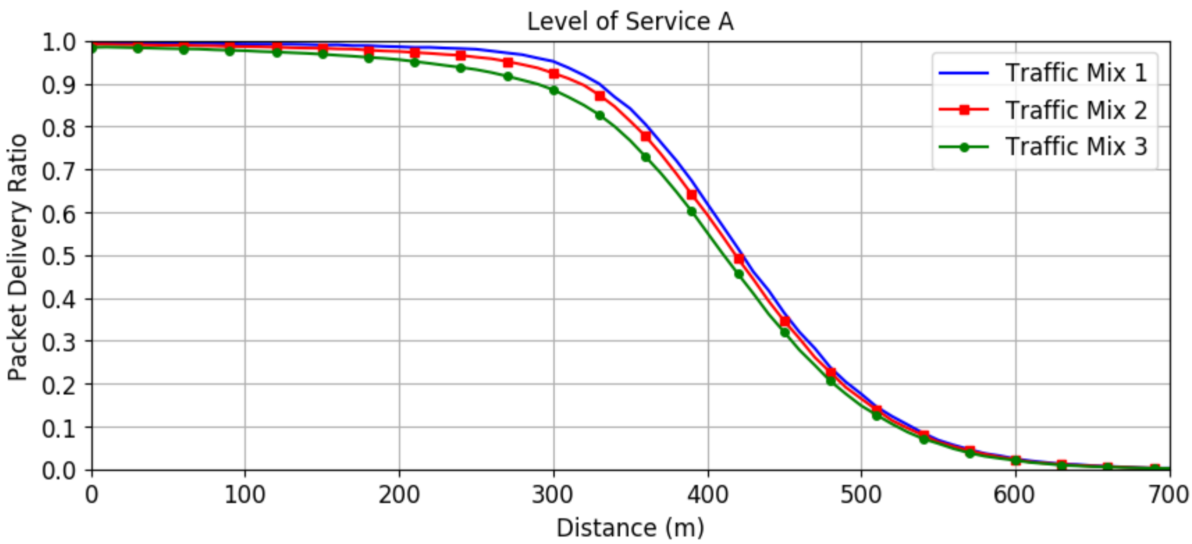
	Traffic mix 1	**Traffic mix 2**	**Traffic mix 3**
LOS A	2.99	5.45	9.23

LOS B	5.54	9.27	16.56
LOS C	12.13	22.26	34.45

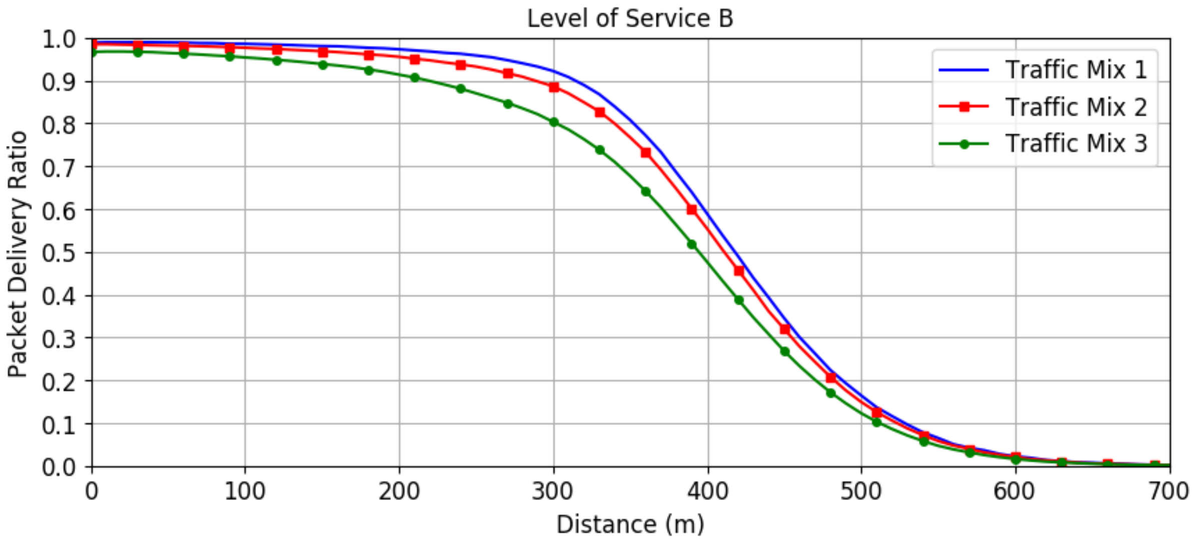
Table 12: Latency for Service 4.2 in motorway scenario.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS A	0.96 ms	1.01 ms	1.09 ms
LOS B	1.02 ms	1.09 ms	1.32 ms
LOS C	1.15 ms	1.53 ms	2.62 ms

Table 12 shows the average latency of all the messages transmitted during the simulation time for the different parameter configuration of traffic mixes and levels of service. The reduced latency values obtained from the simulations show that V2X communications are not impeding the efficient and timely execution of the traffic management measures defined by Service 4.2, as vehicles have enough time to receive message and execute the corresponding manoeuvre in a safe and efficient way.



(a)



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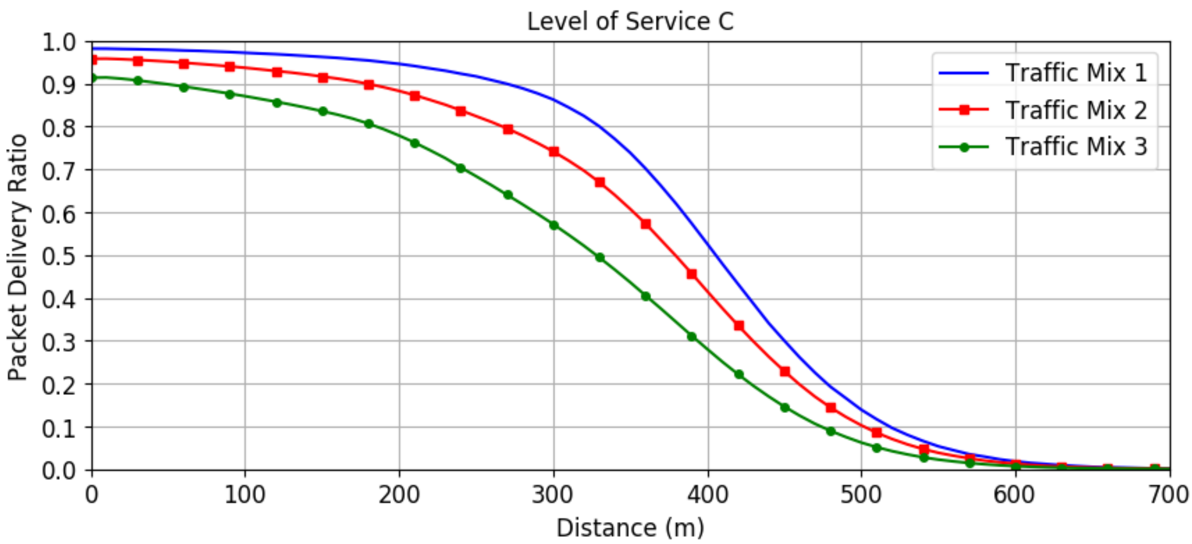


(c)

Figure 23: Packet Delivery Ratio for service 4.2 in motorway scenario.

Figure 23 shows the PDR obtained in the simulation of the motorway scenario of Service 4.2. We observe how the PDR decreases with the increasing density of vehicles with V2X capabilities. This behaviour can be observed comparing the values of the PDR for different traffic mixes within a specific level of service. This is the normal operation of V2X communications that get affected by, e.g., the increasing interference levels and hidden terminal problem.

The overall analysis of the communications KPIs for the motorway scenarios under realistic conditions shows that the execution of the traffic management measures of Service 4.2 does not negatively impact the performance of the V2X communications. However, as shown earlier, the performance of the V2X communications has influenced the traffic KPIs for some specific simulated parameter combinations and seeds. In the remainder, we evaluate these specific parameter configurations.

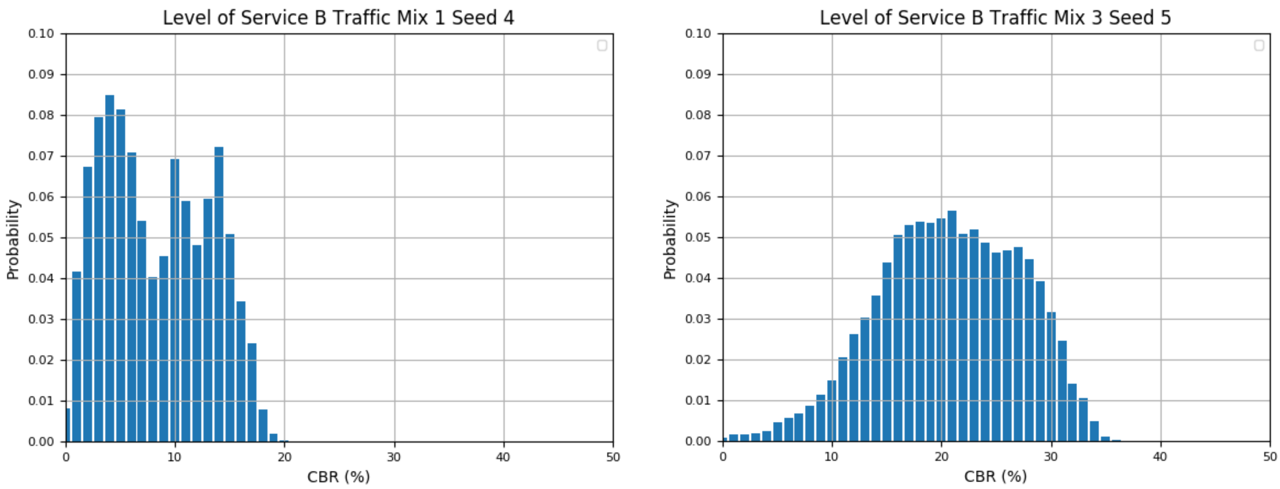


Figure 24: Channel Busy Ratio for the Service 4.2 in the motorway scenario. The left column shows the CBR for LOS B, Mix 1, Seed 4 and the right column shows the CBR for LOS B, Mix 3, Seed 5.

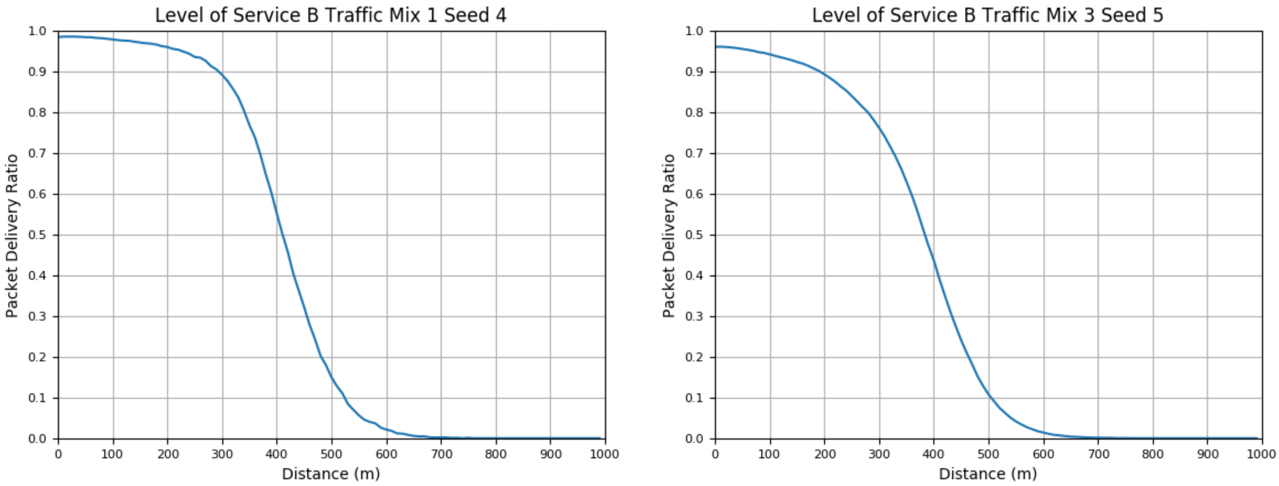


Figure 25: Packet Delivery Ratio for the Service 4.2 in the motorway scenario. The left column shows the PDR for LOS B, Mix 1, Seed 4 and the right columns shows the PDR for LOS B, Mix 3, Seed 5.

Figure 24 shows the histograms of the CBR for the two specific parameter configurations that have shown significant differences in terms of traffic KPIs between the ideal and realistic communications simulations. The results reported in Figure 24 show that the CBR is always below 40 % for both cases. This means that the channel load sensed at any point during the simulation is always below 40 %, and therefore it is not expected to cause a (significant) degradation of the V2X communications performance In this context, the impact of the V2X communications on the traffic KPIs reported above is not due to an excessive channel load but due to propagation errors that result in that some messages are not correctly received. Figure 25 shows the PDR for the same parameter configurations under evaluation. We do not appreciate significant differences for the PDR of these specific configuration parameters in comparison with the average PDR results shown in Figure 23. Despite the high probability of successful message reception, some messages will not be received. The impact on the traffic KPIs of not receiving a periodic message, such as the CAM, is limited since new messages will be received in a relative short time (between 100 ms and 1 second depending on the CAM generation rules). However, the impact of not receiving a message containing an important advice from the infrastructure can produce a disturbance in the traffic flow. For the specific seeds evaluated, the message containing the information for guiding the CAVs to the safe spots has not been received by some CAVs. Thus, those CAVs have performed an MRM in the free lane producing a disturbance in the traffic flow. These results show the importance of the correct reception of infrastructure advice. In the first iteration of the project, the infrastructure advices are sent only once and are not retransmitted in case the CAVs do not correctly receive them. During the second iteration of the TransAID project, we will evaluate different mechanisms to guarantee that the infrastructure advices are correctly received by CAVs while minimising any potential negative impact in the stability and scalability of V2X networks. This could be achieved, for example, with a periodic transmission of the advices that is deactivated when the vehicles acknowledge their reception.

3.4.3 Discussion

The results obtained from the iTETRIS simulations, that encompassed both ideal and realistic communications, were found to be similar with the corresponding results of Deliverable 4.2 [2] for urban traffic conditions. Thus, we identified that communication errors did not impact the successful implementation of traffic management in this case. On the contrary, differences among no, ideal and realistic communications were exhibited for specific parameter combinations under motorway traffic conditions. Specifically, we observed that for realistic communications, CAVs failed to reach safe spots after unsuccessful ToCs for individual simulation replications. However, the latter communication errors adversely affected traffic management only in 2 of the 90 simulation replications (2 %) that were run in total.

Finally, we note that there are still lessons to be learned for several aspects of the scenario, which should be, especially with respect to the real-world prototype, kept in mind for future work:

a) Road-side infrastructure
   - RSU locations should be chosen deliberately with respect to communication radius, communication delay, and traffic management algorithm.
b) RSU software
   - A central traffic management logic (TMC) is assumed which controls the RSUs. Therefore, a direct/wired connection to the physical RSUs is desirable.
   - CAM state information of vehicles should be estimated by TMC in case of missing timely state information.
c) V2X implementation
   - Techniques that assure the correct reception of infrastructure advices should be implemented for a more robust traffic management tolerant to sporadic communications failures.

3.5 Scenario 5.1: Schedule ToCs before No-AD zone

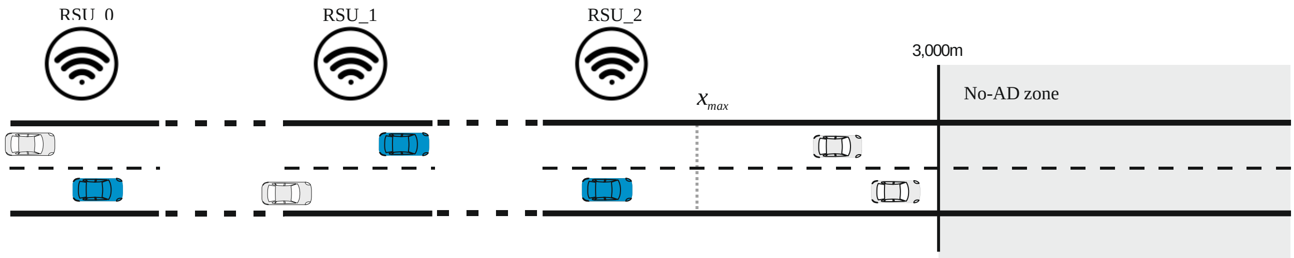


Figure 26: Schematic representation of Scenario 5.

3.5.1 Introduction

In this scenario, we seek to decrease disruptions to traffic flow originating from the accumulation of ToCs at a road section approaching a No-AD zone, where automatic driving is prohibited. As shown in [2], the spatio-temporal distribution of ToCs can have a beneficial effect even for a relatively simple heuristic for this distribution based on the current traffic density and a sequential induction of ToCs for strings of CAVs.

An important consequence of the realistic simulation of V2X communications is the limited range of wireless communication of an RSU. This is especially important for the present scenario as ToC advices potentially have to be administered at arbitrary positions along a relatively long road stretch. Our approach relies on the equidistant placement of three RSUs along the defined approaching area of the 3km-long road segment approaching the No-AD zone (see Figure 26). Their locations are given in Table 13.

Table 13: Location of RSUs in Scenario 5.

RSU ID	Distance from entry point
"RSU_0"	200 m
"RSU_1"	1200 m
"RSU_2"	2200 m

Furthermore, in contrast to the case of perfect and instant information retrieval considered for the development of traffic management procedures presented in [2], the traffic management algorithm now has to rely on information on the vehicle states (position, speed, acceleration, automation mode, etc.) coming in only in more or less regular intervals via CAM messages sent by the vehicles. Less regular reception of state updates might occur, e.g., due to transmission errors, and consequently the traffic management logic has to extrapolate the state from the imperfect information available. This was done in a linear fashion for the present scenario since we expect the algorithm to be rather robust, i.e. the implementation of distribution of ToCs per se should yield already a large benefit, while the precision of scheduled ToC position matters to a lesser degree. That is, minor deviations between the extrapolated states used as input to the algorithm and the reality are likely to change the traffic management efficiency only marginally.

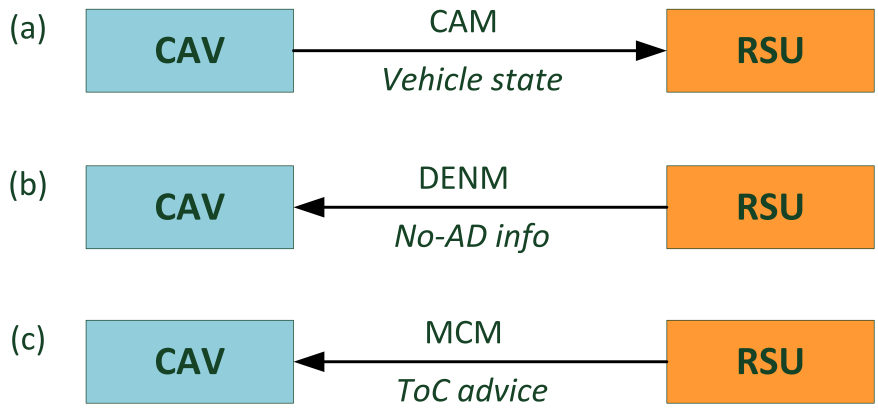


Figure 27: Communications in Scenario 5.

The essential parts of the communication protocol for Service 5 involve three types of message exchange of which two are transmitted by the RSUs (a DENM containing the No-AD info and an MCM containing a ToC advice), and one by the CAVs (CAMs containing the current vehicle state), see Figure 27.

The RSUs send ToC advices to individual vehicles when they are close to the ToC assigned position. Additionally, No-AD info packets are transmitted periodically once per second to all vehicles. These transmissions are taken out synchronously by all three RSUs as triggered by the TM logic, which is assumed to execute at a central location and to be connected to all three RSUs reliably, i.e. by wire. Similarly, received CAMs are centrally processed for all RSUs by the same traffic management program.

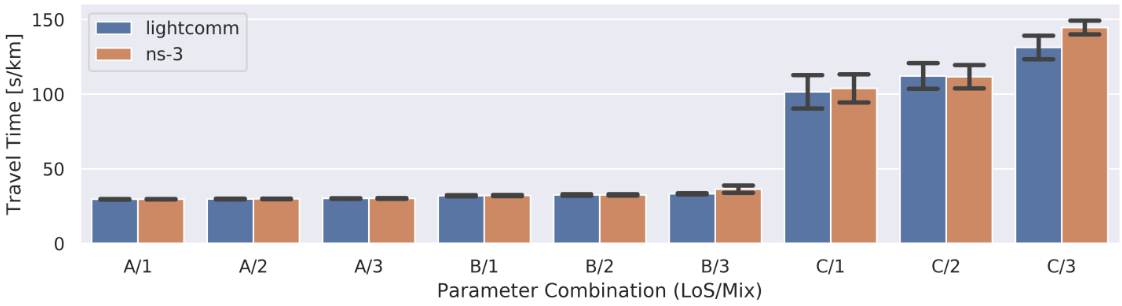
If a CAV receives a No-AD info, it will, *in any case*, take out a transition before entering the No-AD zone, regardless of whether a subsequent ToC advice was received. We assume that only the reception of a ToC advice may cause the vehicle to induce a transition earlier than the latest possible point x_{max} for starting a transition autonomously (see Figure 26), which is calculated to ensure the possibility of a full stop before the No-AD zone even in the case of a failing transition, i.e., if the vehicle has to undertake an MRM. For more information on the protocol, see also [9].

3.5.2 Results

In this section, we present and describe the simulation results obtained for this scenario. The main objective of the performance evaluation is to inspect the robustness of the TM procedures with respect to the simulation of realistic V2X data communication. To this end, we simulated all combinations of scenario parameters (demand level and penetration rate) for both ideal and realistic communication as described in Section 0.

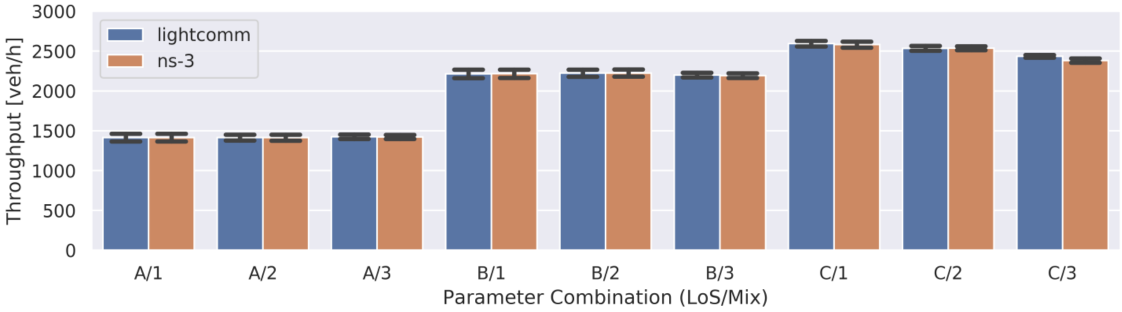
Traffic

As in Deliverable 4.2 [2], we inspected the performance aspects traffic efficiency, traffic safety, and environmental impact, quantified with the network-wide traffic KPIs “travel time” and “throughput”, “critical events”, and “CO_2 emissions”, respectively (cf. [13]). Additionally, we inspected the number of TORs and MRMs, which are specific to TransAID.



lightcomm
ns-3
Travel Time [s/km]
150
100
50
0
A/1
A/2
A/3
B/1
B/2
B/3
C/1
C/2
C/3
Parameter Combination (LoS/Mix)

(a)

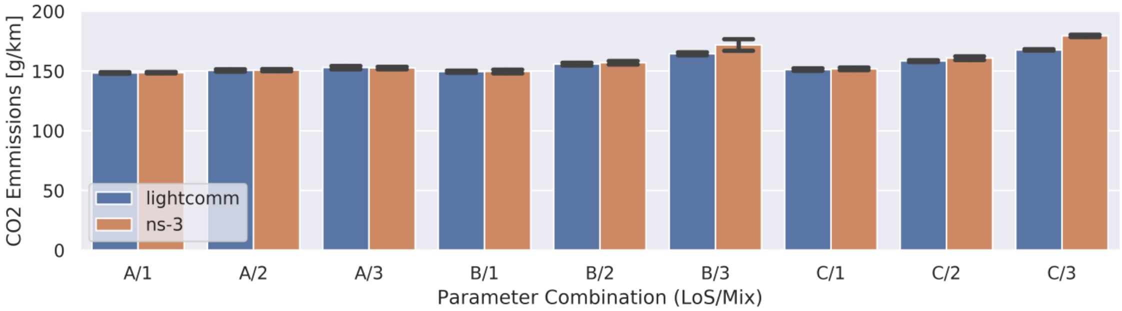


lightcomm
ns-3
Throughput [veh/h]
3000
2500
2000
1500
1000
500
0
A/1
A/2
A/3
B/1
B/2
B/3
C/1
C/2
C/3
Parameter Combination (LoS/Mix)

(b)

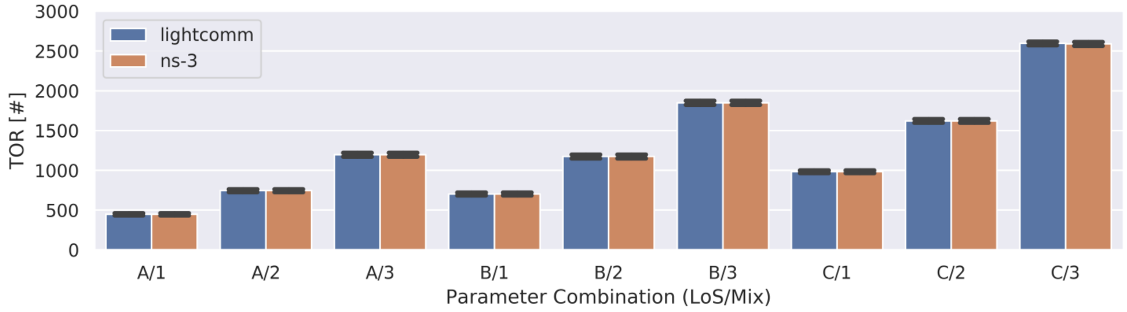
lightcomm
ns-3
Critical Events [#]
100
80
60
40
20
0
A/1
A/2
A/3
B/1
B/2
B/3
C/1
C/2
C/3
Parameter Combination (LoS/Mix)

(c)

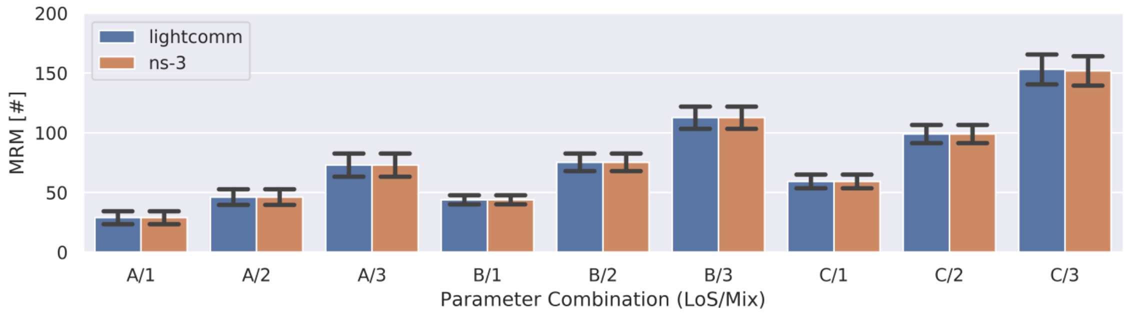


CO2 Emmissions [g/km]
200
150
100
50
0
lightcomm
ns-3
A/1
A/2
A/3
B/1
B/2
B/3
C/1
C/2
C/3
Parameter Combination (LoS/Mix)

(d)



(e)

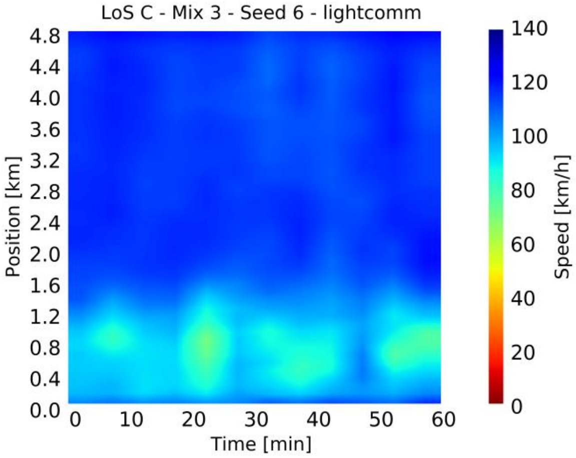


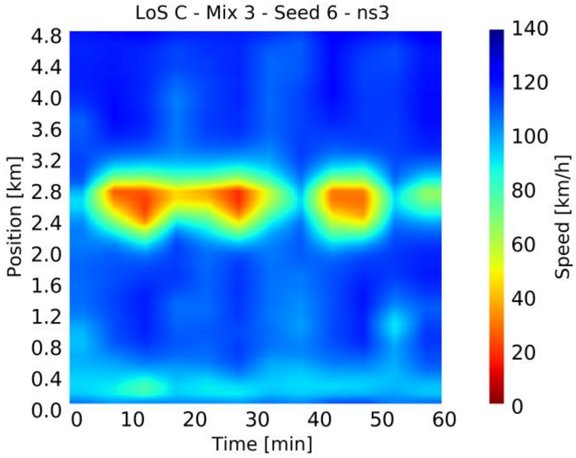
(f)

Figure 28: Network-wide simulation results for use case 5. Error bars show the standard deviation among ten replications over one hour simulation time for the corresponding parameter combination.

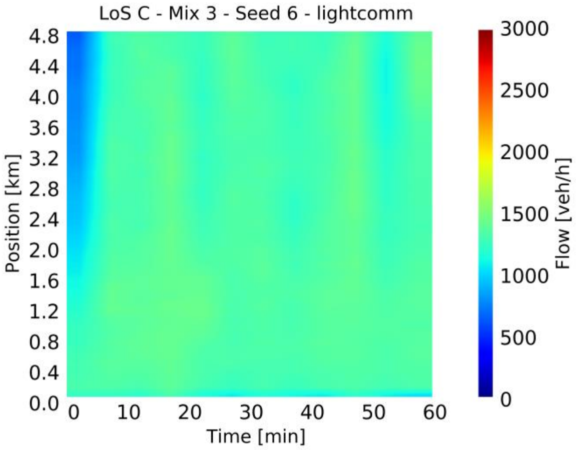
Figure 28 summarises the obtained network-wide simulation results for this scenario. Note that these results cannot be directly compared to the ones presented in D4.2 [2], where baseline and traffic management Service 5 without communication where evaluated, since the longitudinal mark for the entry to the No-AD zone has been moved from 2.5 km to 3 km, resulting in a longer approach stretch. However, similar trends in the results can be observed: Throughput (see Figure 28 (b)) increases with higher LOS while it decreases with CAV shares. Also, the number of critical events (TTC events lower than 3 s), as shown in Figure 28 (c), increases with the level of service but is still negligible in the case of ideal communication (LightComm). Furthermore, CO_2 emissions (see Figure 28 (d)) exhibit no notable differences across levels of service and increase only marginally with higher penetration rate. The travel times shown in Figure 28 (a) suggest that the scenario is only saturated for the highest LOS C since travel times for LOS A and B are comparable but significantly increase for LOS C. Moreover, increasing CAV shares lead to longer travel times in the case of LOS C.

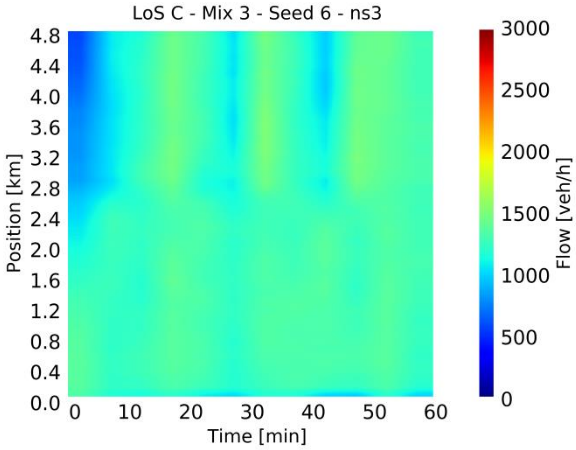
Both the number of TORs and MRMs (Figure 28 (e) and (f), respectively) increase with demand level and penetration rate, which is to be expected as the total number of TORs is directly proportional to the number of CAVs since each CAV performs a ToC *eventually* in this scenario (cf. Section 3.5.1). A TOR then probabilistically leads to an MRM, which explains the dependency of the number of MRMs on TORs. In addition, changing the communication mode from "ideal" to "realistic" has no impact on both of these KPIs since only actually induced TORs are counted here. A vehicle which has not induced a TOR would have received neither any of the No-AD information messages nor an individual ToC advice, which is very unlikely given the scenario.





(a) **(b)**





(c) **(d)**

Figure 29: Exemplary spatio-temporal plots visualising KPIs speed (a, b) and flow (c, d), respectively, for use case 5. For both KPIs, ideal (a, c) and realistic (b, d) communication results are shown side-to-side for easier comparison.

A comparison of the results for ideal (LightComm) and realistic (ns-3) communication most prominently shows a significant impact on critical events (Figure 28 (c)). The levels of service B and C exhibit a significant increase in the number of critical events for the highest penetration rate. Similarly, realistic communication impacts parameter combinations B/3 and C/3 for KPIs travel time and CO_2 emissions (cf. Figure 28 (a) and (d), respectively). This discrepancy can be explained with the current assumption of the ToC scheduling algorithm that communication is error-free. ToC advices are, therefore, sent only once by the scheduling algorithm and consequently might not be received correctly in some cases (also see communication results below). These network-wide results are also supported by local traffic efficiency KPIs speed and flow with spatio-temporal plots as exemplarily shown in Figure 29: speeds just before the entry to the No-AD zone (at 3.0 km) are impaired when considering realistic communication (compare Figure 29 (a) and (b)).

In conclusion, the proposed traffic management algorithm is, in its current form, indeed sensitive to communication errors. However, this flaw can be solved by implementing an acknowledgement mechanism to ensure the correct reception of ToC advices.

Communication

This section evaluates the performance of V2X communications when the traffic management measures of Service 5 are executed. In particular, we evaluate the Channel Busy Ratio, the latency, and the Packet Delivery Ratio. Table 14 shows the average CBR sensed by all the vehicles in the simulation for all combinations of scenario parameters (i.e. level of service and traffic mix). We can derive from the low levels of CBR measured that the traffic management measures executed do not negatively impact the V2X communications for any of the parameter combinations under evaluation. Furthermore, we can observe how the traffic congestion caused by the Level of Service C, that significantly increases the travel time of vehicles (see Figure 28 (a)), does not produce a similar increase in the CBR. This is the case because the generation rules of V2X messages (see Section **Error! Reference source not found.**) adjust the transmission period based on the dynamics and status of the vehicles. For example, when the density of vehicles increases (and consequently their speed reduces), the transmission period of the V2X messages reduces, which results in that the channel load (CBR) is maintained low.

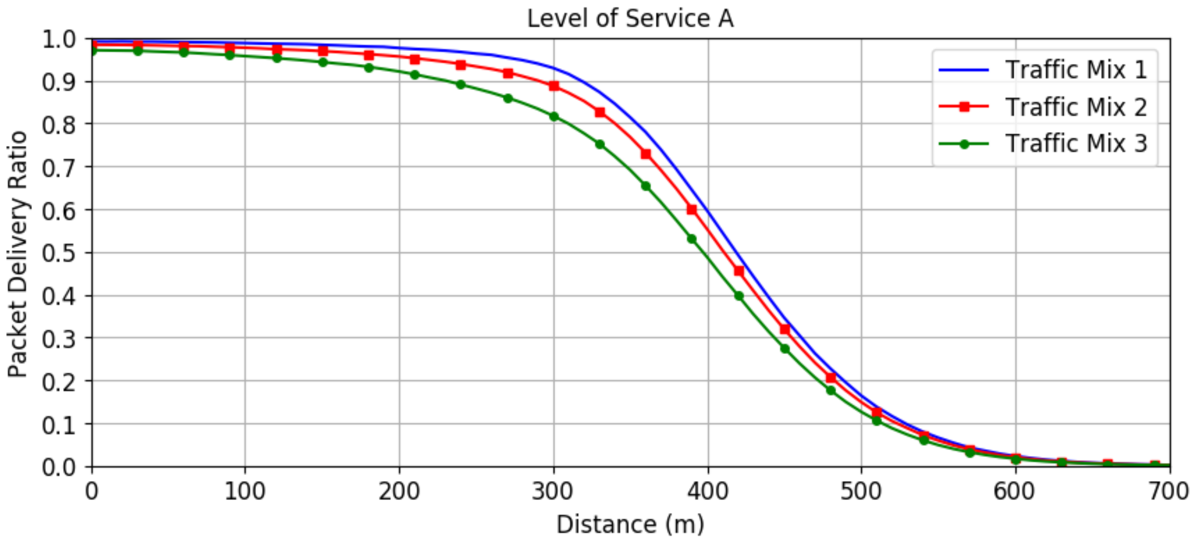
Table 14: Channel Busy Ratio for Service 5.

	Traffic mix 1	**Traffic mix 2**	**Traffic mix 3**
LOS A	4.92 %	8.70 %	14.77 %
LOS B	8.71 %	15.31%	26.65 %
LOS C	10.59 %	18.45 %	31.40 %

Table 15: Latency for Service 5.

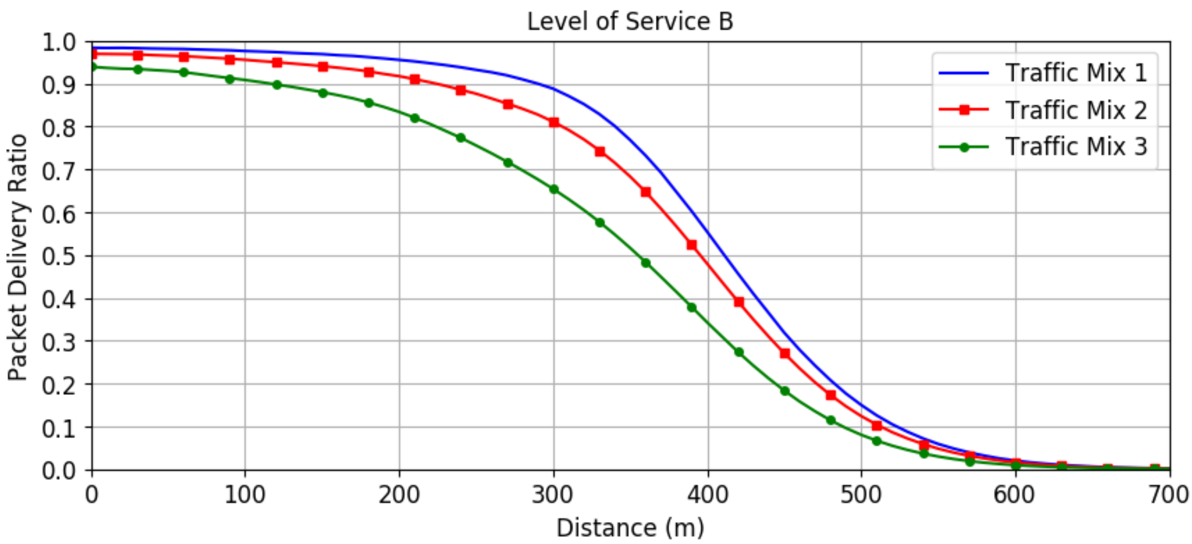
	Traffic mix 1	**Traffic mix 2**	**Traffic mix 3**
LOS A	1.01 ms	1.10 ms	1.28 ms
LOS B	1.10 ms	1.30 ms	1.96 ms
LOS C	1.14 ms	1.40 ms	2.41 ms

Table 10 shows the average latency of all transmitted messages in the simulation. The latency is computed as the time elapsed since the generation of the packet in the ITS Facility layer to the reception of the packet at the receiver side. The short latency measured in the simulations for all combinations of scenario parameters guarantees the timely reception of the V2X messages to safely execute the required manoeuvres defined by the traffic management measures of Service 5.



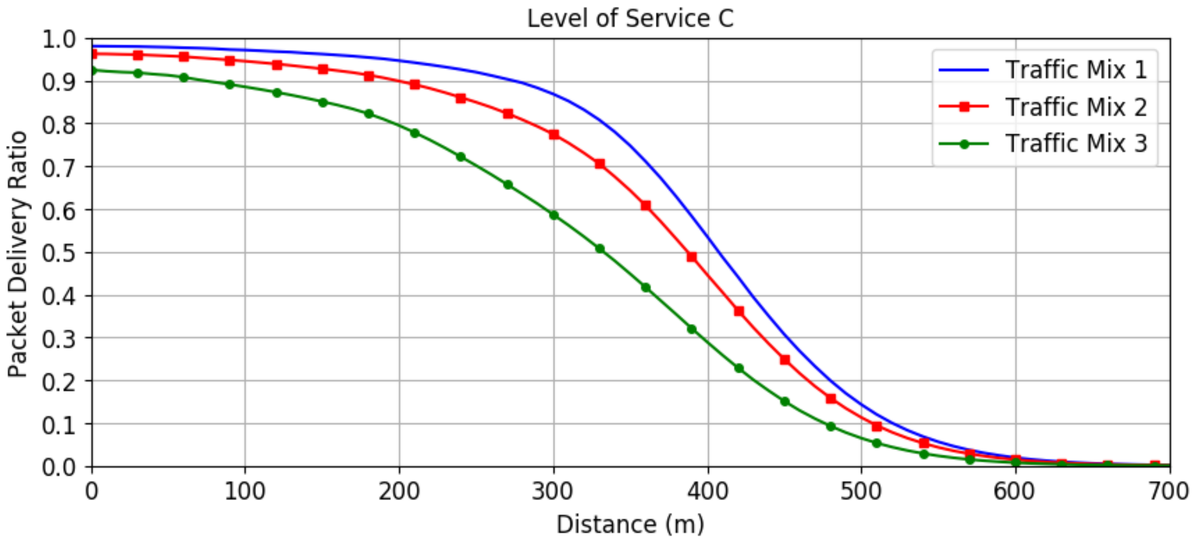
Level of Service A
Packet Delivery Ratio
Distance (m)
Traffic Mix 1
Traffic Mix 2
Traffic Mix 3
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
500
600
700

(a)



Level of Service B
Packet Delivery Ratio
Distance (m)
Traffic Mix 1
Traffic Mix 2
Traffic Mix 3
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
500
600
700

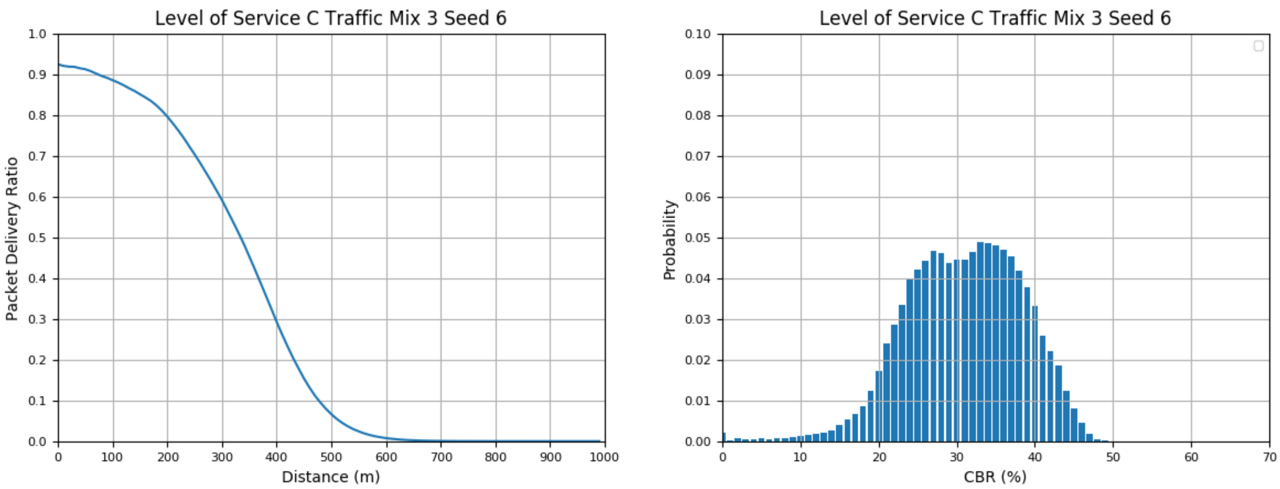
(b)



(c)

Figure 30: Packet Delivery Ratio of Service 5.

The PDR for the different combinations of scenario parameters of the simulations of Service 5 is shown in Figure 30. As expected, the PDR decreases with the distance due to the propagation losses. Similarly, the effects of the increase of the connected vehicles share can be observed comparing the PDR of the different traffic mixes. In this case, for example, the increasing number of connected vehicles, and consequently of V2X messages, results in an increase of interference levels that cause a reduction of the PDR. It is important to take into account that although the majority of the V2X messages are successfully received, some messages can be lost and this can potentially impact the traffic flow as discussed in the analysis of the traffic KPIs for Service 5. In what follows we analyse the same combinations of scenario parameters that produced the traffic disturbance (LOS C, Mix 3, Seed 6) in terms of V2X communications.



(a) **(b)**

Figure 31: Packet Delivery Ratio (left) and Channel Busy Ratio (right) of Service 5 for the parameter configuration LOS C, traffic mix 3 and seed 6.

Figure 31 shows the PDR as a function of the distance and the probability distribution function (PDF) of the CBR measured in Service 5 when LOS is set to C, Mix is 3 and the Seed is 6. The reported results in Figure 31 show only slight differences in the values of the PDR obtained with respect to the average PDR of all the different seeds tested. In addition, the CBR PDF shows that the maximum CBR sensed is below 50 % at any time of the simulation. Therefore, we can infer that neither a higher channel load nor a lower PDR are the cause of the traffic KPI results reported in Figure 28, but simply some lost packet. As stated in the discussion of the traffic KPIs of Services 5, the ToC advices are only sent once, and there are no retransmissions scheduled in case some ToC advices are not correctly received. To guarantee the successful reception at the vehicles of the advices sent by the infrastructure, reliable V2X transmission techniques will be evaluated in the second iteration of the project. Those techniques will be designed to guarantee the reception of the V2X messages without causing a negative impact in the channel load due to excessive transmission of messages.

3.5.3 Discussion

The simulation results obtained after implementing the scenario and traffic management measures within the iTETRIS framework have confirmed the essential results of Deliverable 4.2 [2], i.e., the spatio-temporal distribution of ToCs as proposed by the scheduling algorithm can indeed benefit the traffic flow and improve traffic safety. The comparison of simulations results with ideal and realistic communication has shown a certain sensitivity of some traffic KPIs to communication errors, which was to be expected since the proposed TM algorithm relies on lossless communication signal propagation. However, this can be solved by adding an acknowledgement mechanism in order to make the messaging of ToC advices more robust. This mechanism should take the role-up of groups beginning at the end into account since, usually, the first vehicle enters an RSU's communication range first and, therefore, all ToCs should be delayed at least until the last vehicle acknowledges the ToC advice reception. Another way to further decrease disruptions in traffic flow would be to make the ToC distribution even more sophisticated. We leave this as open challenges for future work.

The conducted analysis has shown that the transmission of the necessary messages to execute the traffic management measures of the TransAID Service 5 does not negatively impact the V2X communications performance measure in terms of the CBR, PDR, and latency.

Finally, we note that there are still lessons to be learned for several aspects of the scenario, which should be, especially with respect to the real-world prototype, kept in mind for future work:

a) **Road-side infrastructure**
   - RSU locations should be chosen deliberately with respect to communication radius, communication delay, and traffic management algorithm. In particular, a trade-off between deployment costs and communication data redundancy should be considered.

b) **Automated vehicle control**
   - No-AD information is received by virtually all vehicles eventually to ensure a downward ToC before entry to the No-AD zone. However, it should be noted that immediate and complete compliance of CAVs with ToCs is assumed here. Possible compliance issues with these requests that might arise for future automated vehicles might heavily disrupt traffic behaviour.

c) **RSU software**
   - A central traffic management logic (TMC) is assumed which controls the RSUs. Therefore, a direct/wired connection to the physical RSUs is desirable.

  - CAM state information of vehicles should be estimated by TMC in case of missing timely state information, which is especially important in this scenario. The current implementation takes this into account which adds to the robustness of the traffic management algorithm.

d) V2X implementation

  - Mechanisms guaranteeing the correct reception of infrastructure advices (such as acknowledgement communication packets (ACKs)) should be implemented for a more robust traffic management (as already discussed above).
  - Synchronous packet transmission by all RSUs assumes they are out of interference range requiring adequate RSU placement and/or the addition of a random backoff mechanism to reduce the interferences between RSUs.

3.6 Conclusion

All five TransAID scenarios considered in the project's first iteration including the proposed traffic management measures were simulated and evaluated with a focus on the impact of realistic V2X communication. For this purpose, the scenarios were ported to the iTETRIS platform where feasible (see Scenario 2.1 in Section 3.2 for an example where this was not feasible). In order to obtain comparable results, the V2X simulation software LightComm was employed to simulate ideal communication in comparison to the realistic communication simulation software ns-3.

In a first verification step, the results obtained for all scenarios when employing ideal communication confirmed the statistical trends of the results from Deliverable 4.2 [2], where no V2X communication was considered. As for comparing ideal with realistic simulation of V2X communication, the simulation results for Scenarios 1.1 and 2.1 have shown that these scenarios are not adversely impacted by realistic V2X communication. Furthermore, scenario 4.2 exhibited no significant impact of realistic communication on traffic KPIs for both urban and motorway traffic cases. However, in the motorway traffic case, a few single simulation runs have shown a sensitivity of the traffic management algorithm (in its current state) to communication errors, which might increase and turn significant for higher traffic demands and/or penetration rates than the ones considered here. Similarly, traffic KPI results for Scenario 5.1 suggest a certain sensitivity of the proposed traffic management measures to realistic V2X communication. For both traffic management algorithms, the origin of this sensitivity was traced to single, non-repeated transmissions of some infrastructure advice messages, which were not correctly received due to errors during wireless signal propagation. These flaws can be fixed by employing a transmission mechanism that ensures the correct reception of these infrastructure advices.

While the usage of the LightComm ideal V2X communication simulation in combination with the iTETRIS framework already increases computation time of the simulation to some degree, the much more detailed V2X communication simulation with ns-3 increases computation time significantly. This resource-intensiveness, coupled with major technical hindrances, is the reason that realistic V2X communication results for Scenario 3.1 were not ready in time for this Deliverable's version. Thus, an inspection of the impact of realistic communication on this scenario was not possible at this point in time, but will be included in a future Deliverable version.

In conclusion, the performance evaluation of the considered scenarios and parameter combinations has shown the following:

- The realistic simulation of V2X communication indeed has an impact on traffic scenarios, which makes them indispensable for a realistic performance evaluation of V2X traffic scenarios.
- Traffic management algorithms need to account for sporadic packet loss of various message types in some way.
- Although important, the realistic modelling and simulation of V2X communication also induces a significant computational overhead. Thus, from a general perspective, a trade-off between computation time and degree of realism should be considered.

4 Recommendations for the Real-world Prototype

4.1 Introduction

The aim of this section is to provide recommendations, based on the results of the integrated simulations (or “the virtual prototypes”, see Section 3), that can be implemented in the real-world prototype (WP7). The recommendations are provided for the following four categories:

1. Results of infrastructure models will provide input for the road-side infrastructure.
2. Results of AV behaviour models will provide input for the automated vehicle control.
3. Results of traffic management algorithms will provide input for the RSU software.
4. Results of communication protocols will provide input for the V2X implementation.

For each category, the observations and results per use case form the underlying basis for the recommendations. For details on this basis, see the different scenarios’ “Discussion” subsections of Section 3.

4.2 Road-side Infrastructure

This section deals with the results of the infrastructure models that are used to generate input for recommendations for the (use of) road-side infrastructure.

Infrastructure models are inherently part of the simulations of the use cases considered in TransAID. Geographical parameters, e.g., lane lengths, lane drop locations, merge areas, and placement of RSUs all contribute to the results of the use cases’ simulations. Furthermore, the setup of the infrastructure models is intertwined with the particular setup of AV behaviour models, traffic management algorithms, and communication protocols within these use cases and will, therefore, impact the results of the simulations. Consequently, the same attention should be paid to the real-world road-side infrastructure. In particular, experience with the use cases has shown that RSU placement and their type of connection to the central TMC should be taken into account.

4.3 Automated Vehicle Control

This section deals with the results of the AV behaviour models that are used to generate input for recommendations for the (use of) automated vehicle control.

Driver models were developed to emulate vehicle automations for CAVs/CVs (WP3). These models describe CAV/CV longitudinal motion, lateral motion, and driving behaviour during ToC/MRM. Baseline simulation experiments encompassed three distinct dimensions (traffic demand level, traffic mix, and driver model parametrisation scheme) to capture the effects of ToCs/MRM for varying traffic conditions, traffic composition, and vehicle properties. The analysis of the simulation results (WP3) indicated that congestion at lane drops is highly correlated with safety-critical events. Moreover, we found that traffic safety is further undermined as the share of CAVs/CVs in the traffic mix increases. Simulation results also show that there is no clear relationship between lane-changing and traffic efficiency. However, it is stressed that no investigation was conducted with respect to the allocation of lane changes per advice, location, and vehicle type. This work will be done in future deliverables to identify the impacts of lane changes in the proximity and along TAs. Finally, we demonstrated that emission levels decrease for improved traffic efficiency and increase significantly for stop-and-go traffic.

According to simulation results of WP3, it is clear that traffic operations significantly degrade at lane drop locations leading to adverse impacts on traffic efficiency, safety, and the environment. Thus, facilitating merging operations at lane drops by providing lane advice seems to be a promising measure for improving traffic conditions at TAs, and consequently this should be tested in the real-world environment.

Human driver behaviour after a ToC was modelled in WP3, whereby these aspects influence the overall traffic performance. However, it should be noted that we assumed immediate and complete compliance of CAVs with TORs and, if feasible, the impact of this assumption should be verified with the real-world prototype tests. Nevertheless, the traffic management strategy could persist despite upcoming communication issues in case human driver/vehicle automation perform way better than modelled for the simulations.

4.4 RSU Software

This section deals with the results of the traffic management algorithms that are used to generate input for recommendations for the (use of) RSU software.

The traffic management strategy is based on assumptions about the actual traffic density estimated from current vehicle positions (WP4). Inaccuracies, delays, or low update rates of these vehicle positions (CAM messages) could decrease the traffic management performance based on these traffic state assumptions. Therefore, it is necessary to collect information about the traffic composition and about the position and dynamics of the vehicles on the road. This information is locally gathered by the RSUs and from the CVs and CAVs through collective perception. The CAVs and CVs can send information about themselves, but also information about other vehicles or detected obstacles. Similarly, the RSU will send information about detected vehicles and obstacles to CVs and CAVs in order to enlarge their environmental perception. This information should be transmitted periodically in order for all relevant actors to always be aware of the traffic conditions, as was demonstrated in various V2X message formats (WP5). As a back-up strategy, in case that timely state info is missing, CAM state info of vehicles should be estimated by the TMC.

Additionally, some Services require the coordination of cooperative manoeuvres for CAVs. This can be done both locally by the coordination between the affected vehicles, and they can be assisted by RSUs taking advantage of its inherently larger perception of the environmental scope. To allow the coordination between vehicles, it is necessary that they periodically transmit their future trajectories, so that other vehicles can compare their own trajectories with the received ones and predict potential problematic situations that can be avoided through cooperative manoeuvring. This, however, is a highly time-critical issue. Automated vehicles plan a spacious set of trajectories within milliseconds for the next discrete time frame to determine their next step. From an automation point of view, it might be nearly impossible to transmit one certain trajectory (for a larger time frame of seconds) with a confidence level high enough so that other vehicles can take it into account. This by itself poses some technical challenges. Within simulations of the use cases, vehicles send trajectories and the RSUs send target lane and speed advices, all via manoeuvre coordination messages (MCM).

During simulations, the controlling of RSUs is assumed to be done by logic embedded in a TMC. In order to come to reliable control, it is desirable that the connection of physical RSUs is direct/wired.

Parametrisation of the traffic management application (WP5) also factors in assumptions about CAV behaviour (headways, braking rates, response times, etc.). These parameter sets are rather speculative at the moment and should be verified during the real-world prototype testing.

4.5 V2X Implementation

This section deals with the results of the communication protocols that are used to generate input for recommendations for the (use of) V2X implementation.

The TransAID projects aims to design traffic management measures for TAs with mixed traffic compositions. The use of V2X communications is of key importance to facilitate the cooperation among vehicles and between vehicles and the infrastructure. The definition of the message sets used within the use cases is based on a large list of requirements (following an extensive research of state-of-the-art of V2X messages defined by standardisation bodies or related research projects, and taking the storylines of the TransAID Services into account). This resulted in proposals for extensions of CAMs, DENMs, and MAPEMs. In addition, we proposed an extension of the ETSI ITS Manoeuver Coordination Service allowing the inclusion of RSI suggestions.

Based on the results of the simulations of use cases that are part of this WP, we found that the robustness of the communication protocols ensured that missing a significant part of the messages (e.g. 12.96 % on average for UC 2) did not result in a significant change of performance. The planning of the RSU location greatly assisted in keeping optimal coverage in the area where it is really important. Furthermore:

- Techniques that guarantee the correct reception of infrastructure advices should be designed to make the traffic management measures more robust against sporadic V2X communications failures.
- Synchronous packet transmission by all RSUs assumes they are out of interference range. Adequate RSU placement should be implemented or random back-offs should be added to reduce the interferences between RSUs.
- The frequency of retransmission of the infrastructure advices should be further studied to guarantee the correct reception of them while keeping the channel load as low as possible to avoid negatively impacting the performance of V2X communications.

Therefore, these communication-related findings should be addressed (or at least taken into account at setup) during the real-world prototype tests.

4.6 Overall Recommendations

Since the results of the simulations of the use cases throughout WP3 – WP6 are based on assumptions, the real-world prototype testing in WP7 can be used to either verify the in the previous sections of this chapter mentioned assumptions and findings, or to adjust them. To do so, we advise that the real-world prototype setup is as closely related to the simulated use case descriptions as possible (if feasible). The closer the setup of the real-world prototype to the simulated use cases, the more justified the verification is.

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