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 and second iterations. 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 TransAID scenarios' traffic KPIs were affected, the realistic simulation of V2X communication has shown a discernible impact on some of them, which makes it an indispensable modelling aspect for a realistic performance evaluation of V2X traffic scenarios. Flaws of the first iteration's traffic management algorithms concerning wireless V2X communication and the accompanying possibility of packet loss were identified and have been 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.

We conclude that all results obtained for all scenarios when employing ideal communication confirmed the statistical trends of the results from the original TM scenarios as reported in Deliverable 4.2 [2] where no V2X communication was considered. Furthermore, the performance evaluation of the considered scenarios and parameter combinations has shown the following, which held true in both the first and second iterations:

- The realistic simulation of V2X communication 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.

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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 impact 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 input, high complexity situations etc. In 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 in 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 in 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 use cases. To this end, models for automated driving and ToC/MRM are adopted and developed. The simplified use cases are used for conducting several simulation experiments to analyse the impact of ToCs in 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 use cases will be increased and the possibility of combining multiple simplified use cases into one new more complex use case will be considered.

1.2 Purpose of this Document

Simulations performed and evaluated within the TransAID project have covered baseline scenarios providing reference values for different performance indicators in the absence of traffic management procedures in WP3 (see [1]), and prototypic simulations including traffic management procedures developed in WP4 (see [2]). However, in favour of a rapid proof of concept, communication between vehicles and road side infrastructure was 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 use cases 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 use cases defined in TransAID's first and second 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 use cases resulting from difference between realistic and ideal communication. In addition to this assessment of communication impact for all use cases, 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 use cases 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. Sections 3 and 4 (for the project's first and second iteration, respectively) comprise use case-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 5, 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 use cases, 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 mock-up 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 simulations here presented have been conducted using the iTETRIS platform [4] which is been evolved and extended within the framework of the TransAID project. The complete simulation framework of the iTETRIS platform is shown in Figure 1.

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 use case (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 mock-up 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.

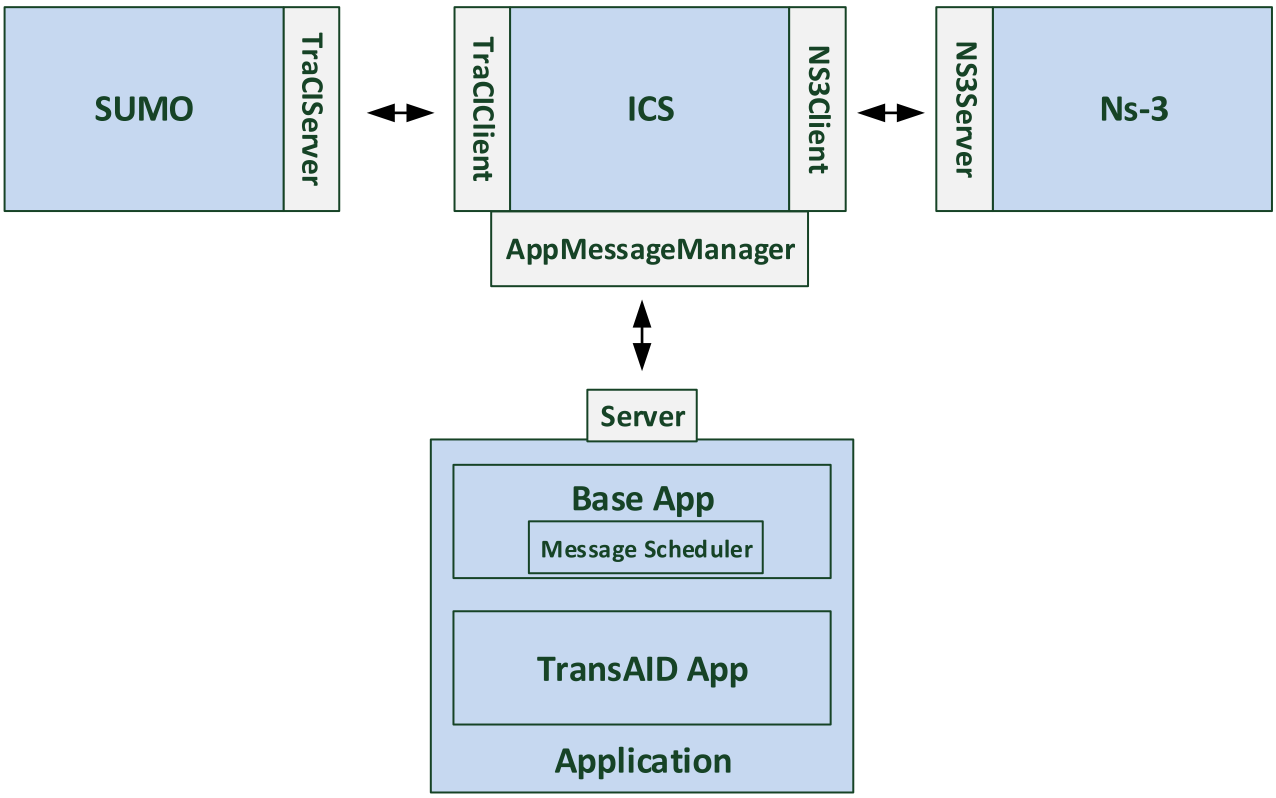


Figure 1: TransAID iTETRIS simulation framework.

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.

[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).

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 use cases 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 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 use cases 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].

2.2.3 Adaptation of CAV Models in iTETRIS

In the simulation experiments that were conducted with the use of the iTETRIS framework during the first project iteration we used vehicle and driver models for CAVs that did not require vehicular communications. However, in the second project iteration we considered CACC equipped vehicles and cooperation capabilities between CAVs for the respective simulation experiments. Thus, the operation of the latter CAV models in iTETRIS should be based on the exchange of the necessary communication protocols. To this end, adaptations were made to CACC car-following model and cooperative lane change model to address the needs of iTETRIS simulations. The aforementioned adaptations were initially presented in [13], but are comprehensively described in this deliverable.

CACC activation/deactivation relies on CAM reception from the leading vehicle. Hence, successful CAM reception by the following vehicles had to be evaluated on the Application side of iTETRIS to switch on/off CACC. The timer approach presented in [13] was eventually adopted for the conduct of the latter task in iTETRIS. Therefore, if CAMs were not received by the following CAVs consecutively for a predefined number of simulation steps (10 steps = 1.0 sec in our experiments) then CACC car-following mode was deactivated. On the other hand, the reactivation of CACC required the reception of CAMs for the same number of consecutive simulation steps to ensure stable operation of the CACC car-following algorithm.

Additionally, changes were made to the triggering of CACC algorithm based on the transmission range of CAMs. In baseline and traffic management simulation previously conducted with the explicit use of SUMO (ideal communications) [1], [2], CACC triggering was assessed according to time headway between CAVs. On the contrary, in iTETRIS the logic of CACC car-following model was restructured so that triggering occurs based on space headway (coinciding with reliable transmission range of CAMs). Thus, CAVs identify leading vehicles within a pre-specified range (300 m in our simulation experiments) using mobility information via CAMs and CPMs from surrounding traffic. If CAMs from leading CAV are received and the timer approach rules hold, then the following CAV can enable CACC. Otherwise, it checks if the leading CAV is within sensor range (120 m in our simulation experiments) when it can apply ACC, or beyond sensor range when it applies Cruise Control (CC) mode (driving with desired speed). The adapted control logic of CACC triggering in iTETRIS is depicted in Figure 2.

The latter changes in the control logic of the CACC algorithm in iTETRIS have also significant implications with respect to simulation results. Previously, CACC activation occurred for time headways lesser than 1.5 sec [1]. Thus, the space headway between two consecutive CAVs in CACC mode would be lower than 300 m in both urban and motorway traffic conditions prior to CACC activation. On the other hand, CACC activation in iTETRIS can occur when two consecutive CAVs are far apart (300 m). Therefore, car-following can be more proactive, smooth, and stable given the larger space horizon for adaptations to speed changes of the leading vehicle. The enhanced car-following behaviour in the iTETRIS simulations yields significant improvements for traffic efficiency, safety, and the environment. The degree of improvement can be observed by comparing simulations results for Use Cases 2.3 and 4.2 (ones simulated with adapted CAV models for communication in iTETRIS) reported in [2] and this deliverable.

Finally, cooperative lane changing between CAVs in iTETRIS is based on the successful exchange of MCMs. If a CAV desires to make a lane change and surrounding conditions are favourable (as described in [13]), then the CAV sends MCM to the nearby blocking CAV to request cooperation. If the blocking CAV accepts the request (we assume this is always the case in our simulation experiments) and transmits back an acknowledgment (MCM) which is received by the CAV desiring to change lane then cooperative lane changing commences. Unless the acknowledgment is received by the latter CAV cooperative lane changing is not possible. If cooperation is not possible due to communication issues in the current time step but the CAV continues to desire the lane change, MCM will be transmitted again in the following time steps as long as the desire to change lane and favourable surrounding conditions prevail.

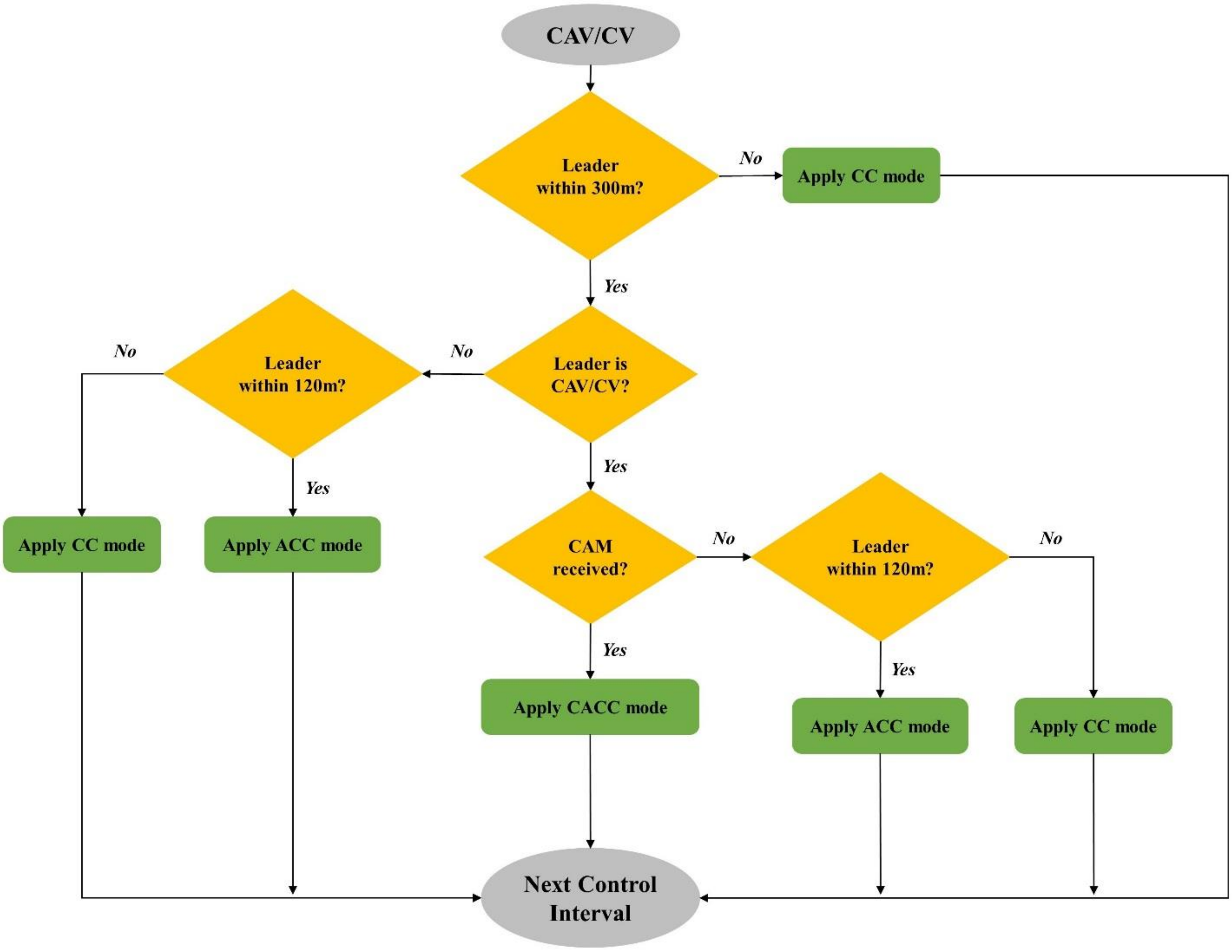


Figure 2: Triggering conditions of different car-following models for CVs/CAVs in iTETRIS.

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.

[14]) for the simulated use case. Based on the aggregated output, graphs are automatically generated (see Figure 3).

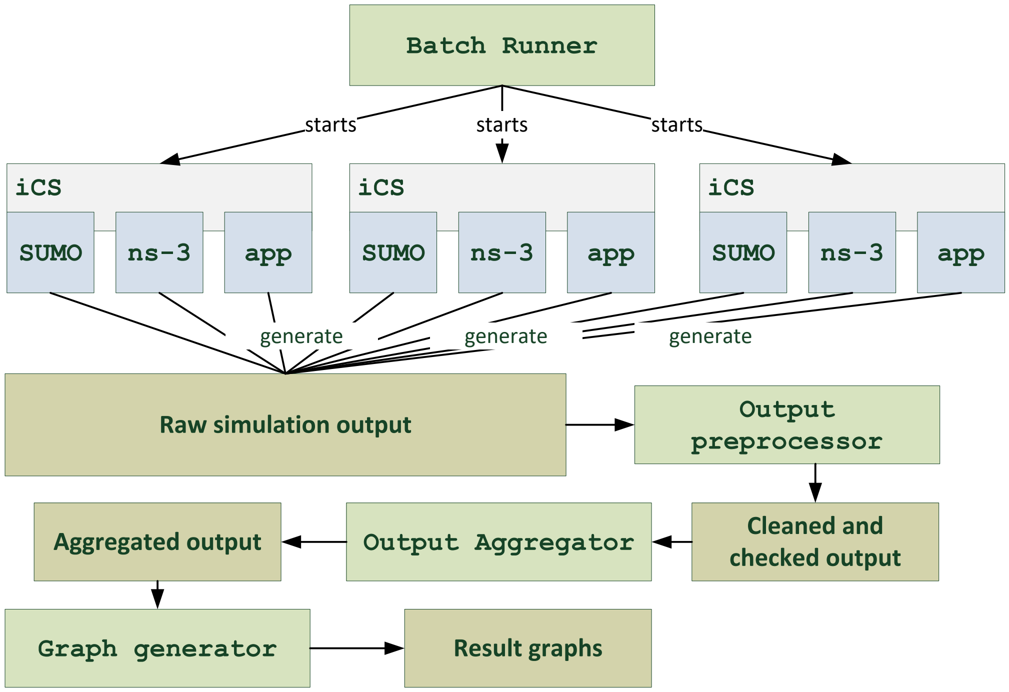


Figure 3: TransAID toolchain (overview of processing stages).

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 use case, 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 Use Case Simulations - First Iteration

3.1 Use Case 1.1: Provide path around road works via bus lane

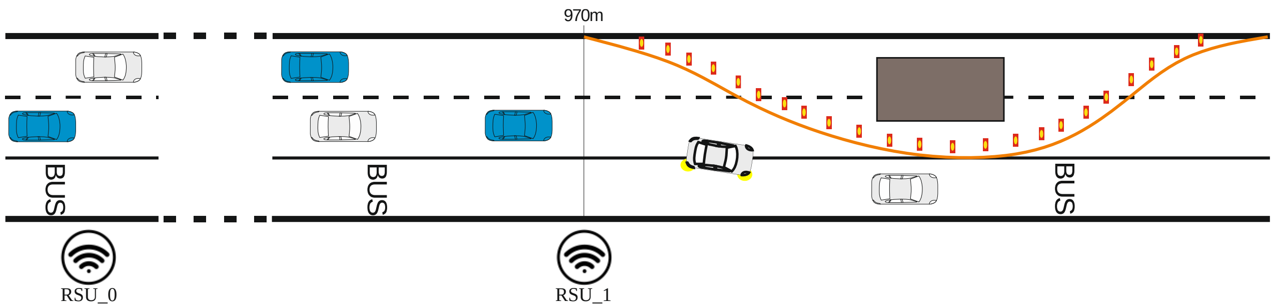


Figure 4: Schematic representation of Use Case 1.1.

3.1.1 Introduction

Use Case 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 4, 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 use case, 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 4). 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 4). Their precise positioning can be gathered from Table 2.

Table 2: Placement of RSUs in Use Case 1.1.

RSU ID	Distance from entry point
“RSU_0”	650 m
“RSU_1”	970 m

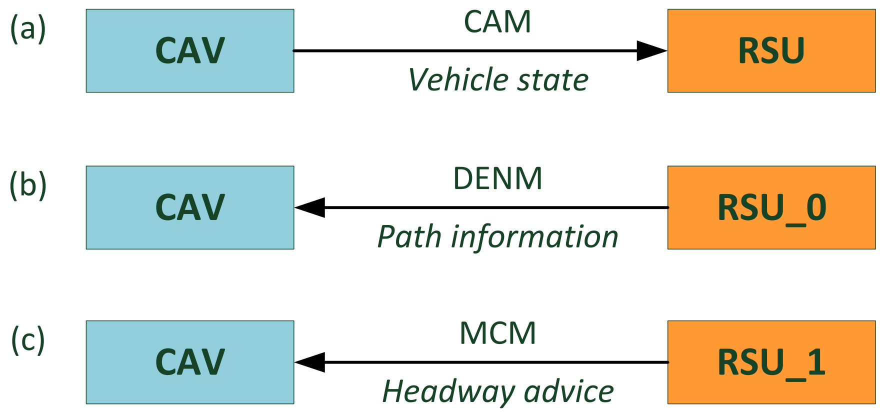


Figure 5: Communication overview of Use Case 1.1.

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 use case 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 5):

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

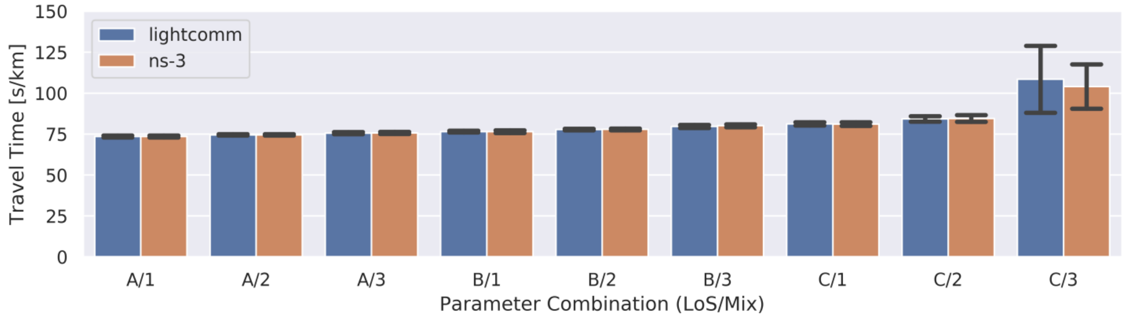
In the following, we present the simulation results obtained for this use case. The main goal of the assessment is to determine the robustness of the traffic management procedures with respect to the inclusion of realistic communication processes. Thus, we simulated all combinations of use case parameters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

Traffic

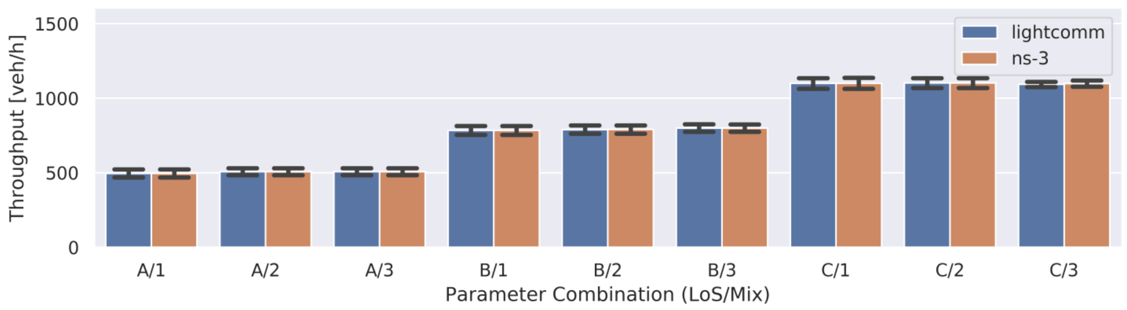
As in Deliverable 4.2 [2], we inspected the performance aspects of traffic efficiency, traffic safety, and environmental impact, quantified with the network-wide traffic KPIs “travel time” and “throughput”, “critical events”, and “CO_2 emissions”, respectively (cf. [14]). Additionally, we inspected the number of TORs and MRMs, which are specific to TransAID.

Figure 6 summarises the network-wide simulation results for this use case. 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.

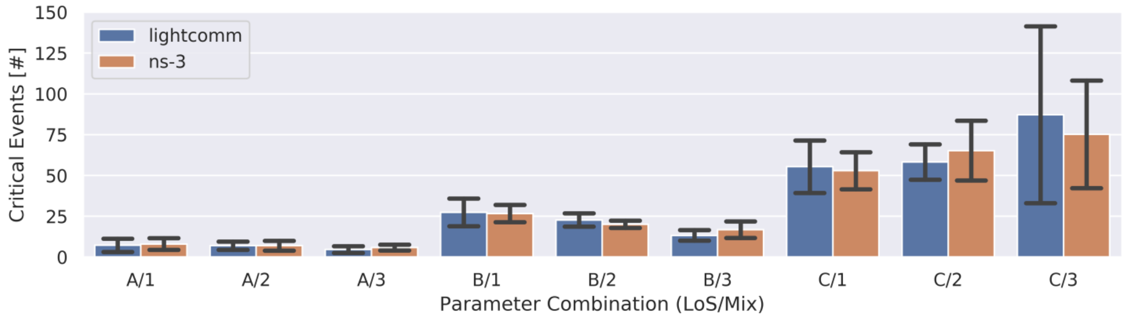
Apart from the verification of earlier results, we observe no significant differences between the results for ideal (“LightComm”) and realistic (“ns-3”) communication (cf. Figure 6). Even though some communication errors occur when ns-3 is used, no significant impact on the selected traffic KPIs can 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 7) supports this conclusion as no significant differences can be made out between the two communication modes.



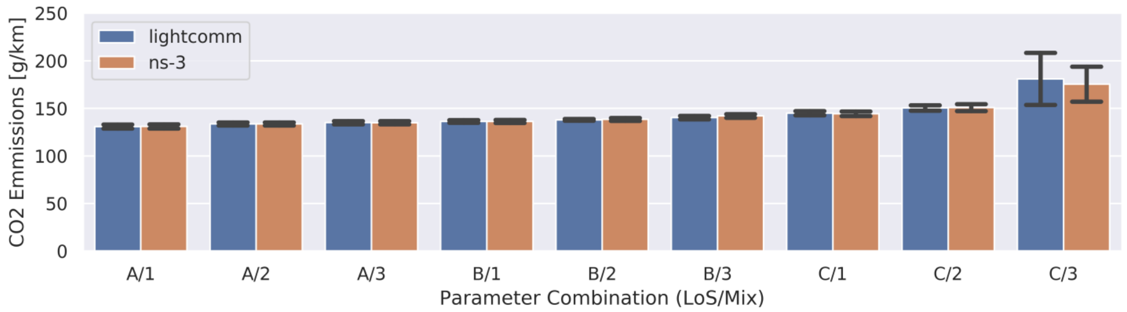
(a)



(b)



(c)



(d)

Figure 6: Network-wide simulation results for Use Case 1.1. Error bars show the standard deviation among ten replications over one hour simulation time for the corresponding parameter combination.

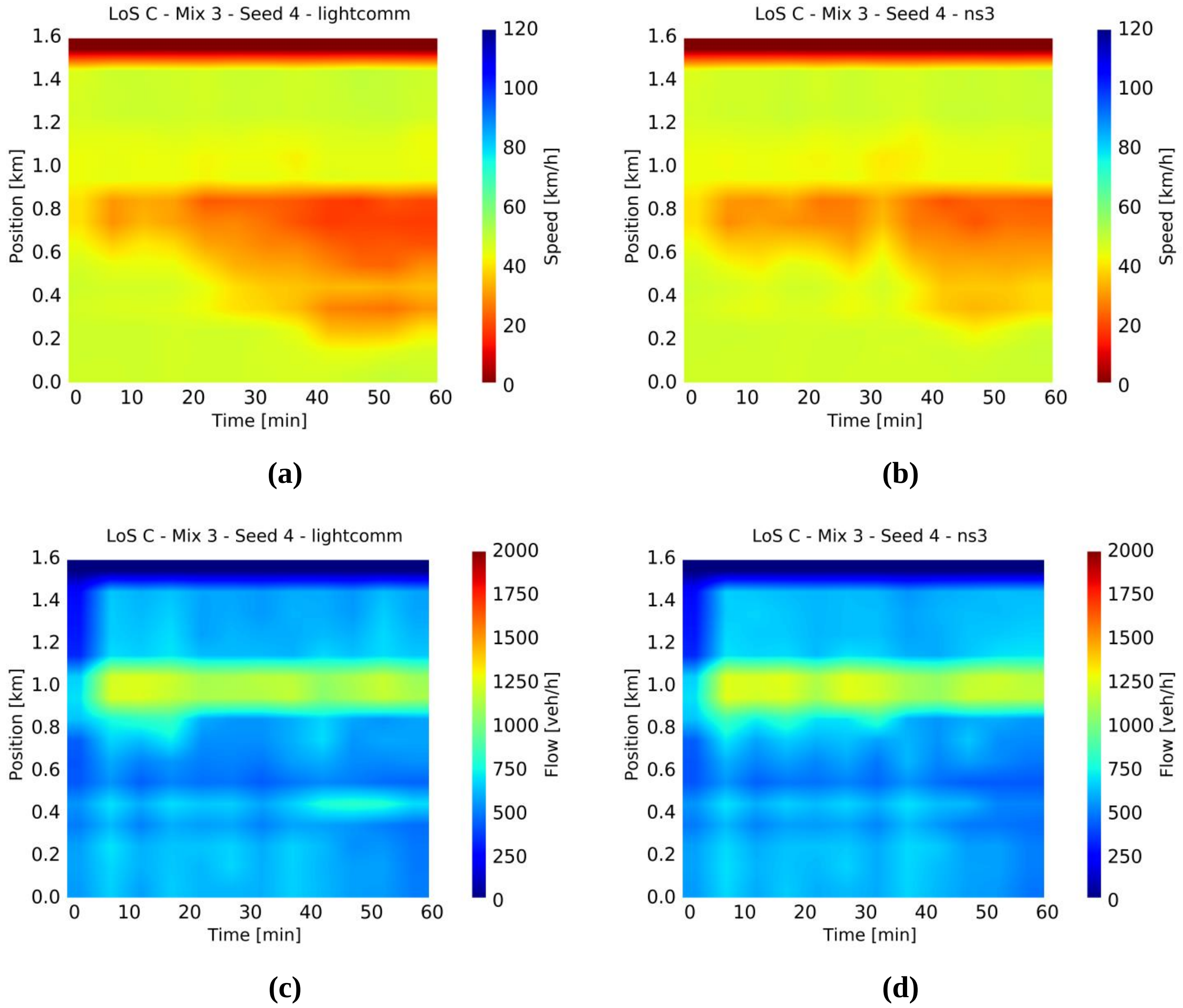


Figure 7: Example spatio-temporal plots visualising KPIs speed (a, b) and flow (c, d), respectively, for Use Case 1.1. For both KPIs, ideal (a, c) and realistic (b, d) communication results are shown side-to-side for easier comparison.

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 use case 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 use case 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 Use Case 1.1 / Service 1 are not creating an excessive V2X communication load and vehicles can access the channel to transmit their messages.

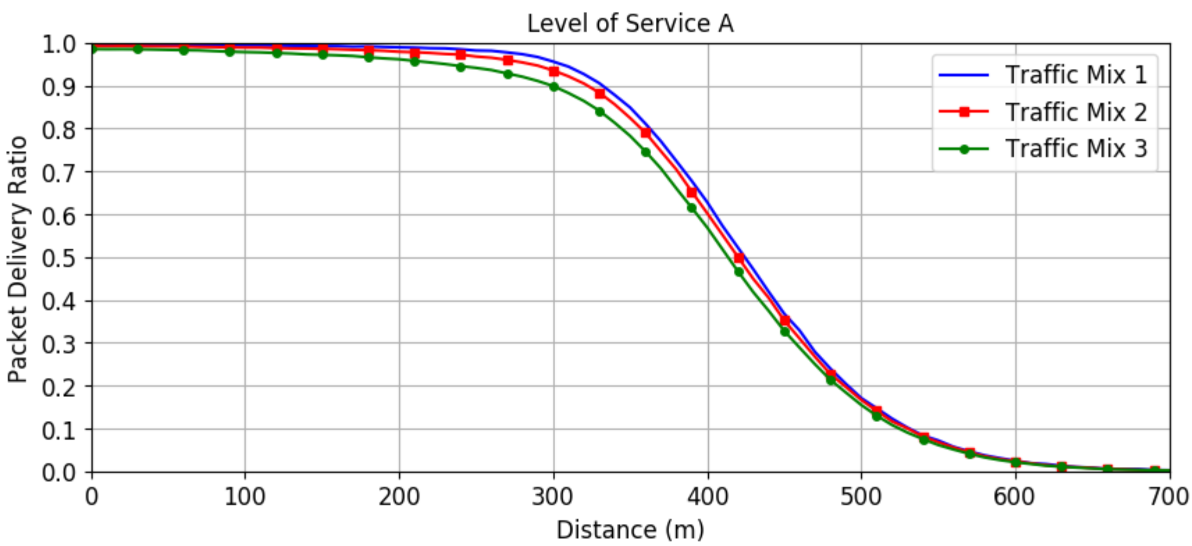
Table 3: Channel Busy Ratios for Use Case 1.1.

	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 %

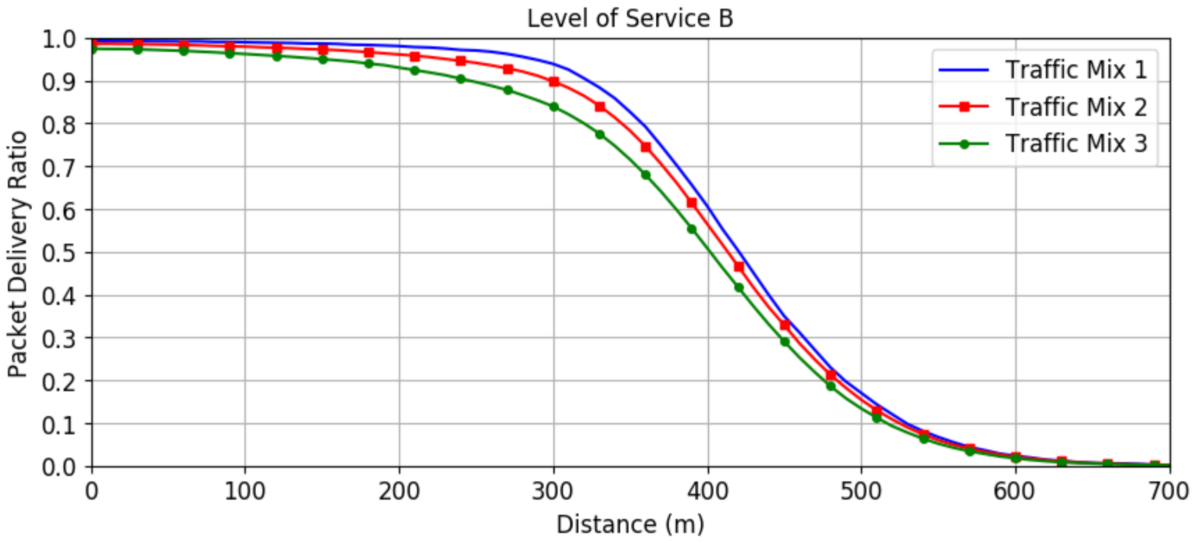
Table 4: Latencies for Use Case 1.1.

	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

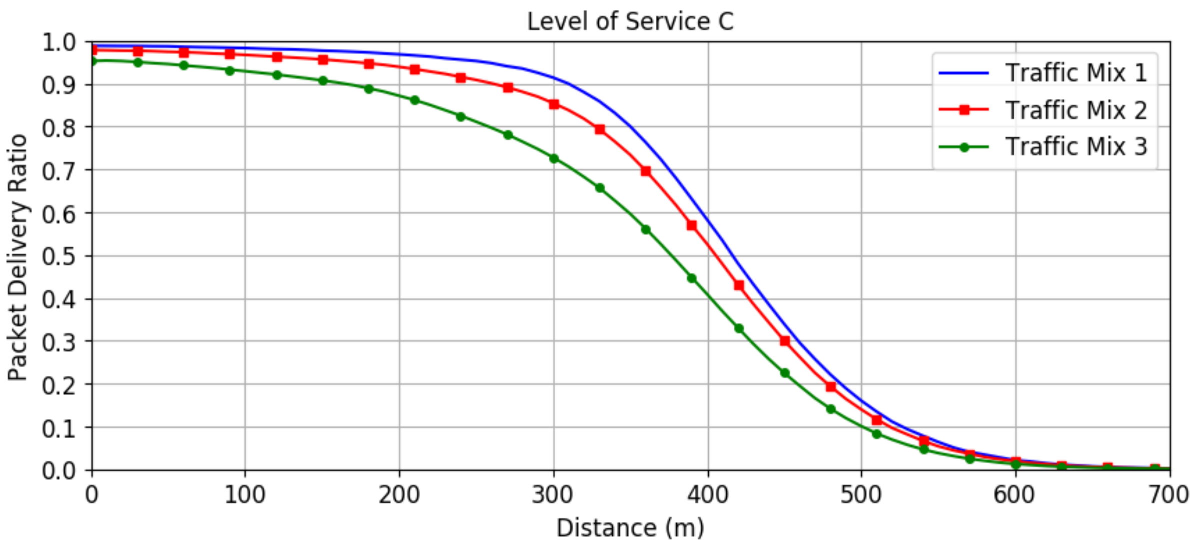
Table 4 shows the average latency of the V2X communications performed during the simulations of Use Case 1.1. The latency measures the time elapsed between the transmission and reception of a packet at the application/facility layer. We can observe that the average latency measured for all combinations of use case 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)



(b)



(c)

Figure 8: Packet Delivery Ratio of Use Case 1.1.

Finally, Figure 8 shows the PDR for the three different levels of service simulated in Use Case 1.1. 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 8 also includes the results obtained for traffic mixes in order to analyse the effects of increasing the number of CVs and CAVs in the use case. 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 use case, 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 Use Case 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 use case 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 use case 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 use case, 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 Use Case 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 use case is shown in Figure 9.

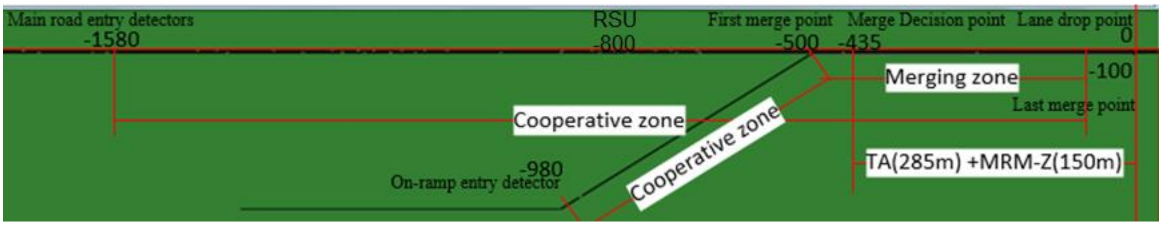


Figure 9: Motorway merging use case.

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 10 shows the message flow employed in the implementation of Service 2.1 in the first iteration of the project.

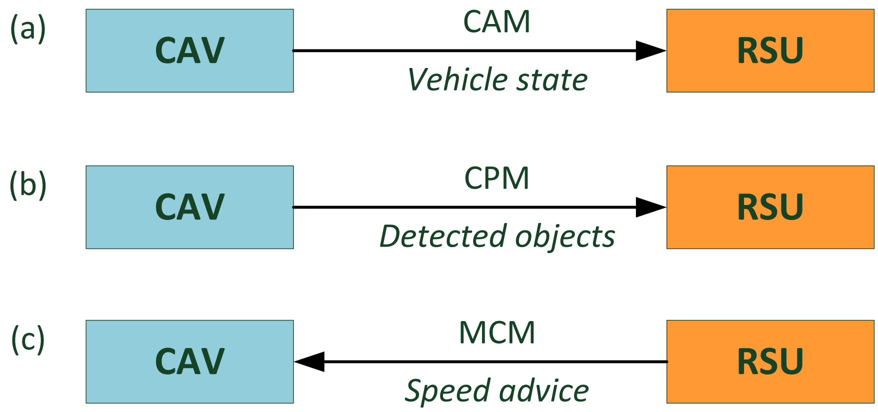


Figure 10: Communications in Use Case 2.1.

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 [15], 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 are 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 use case 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.

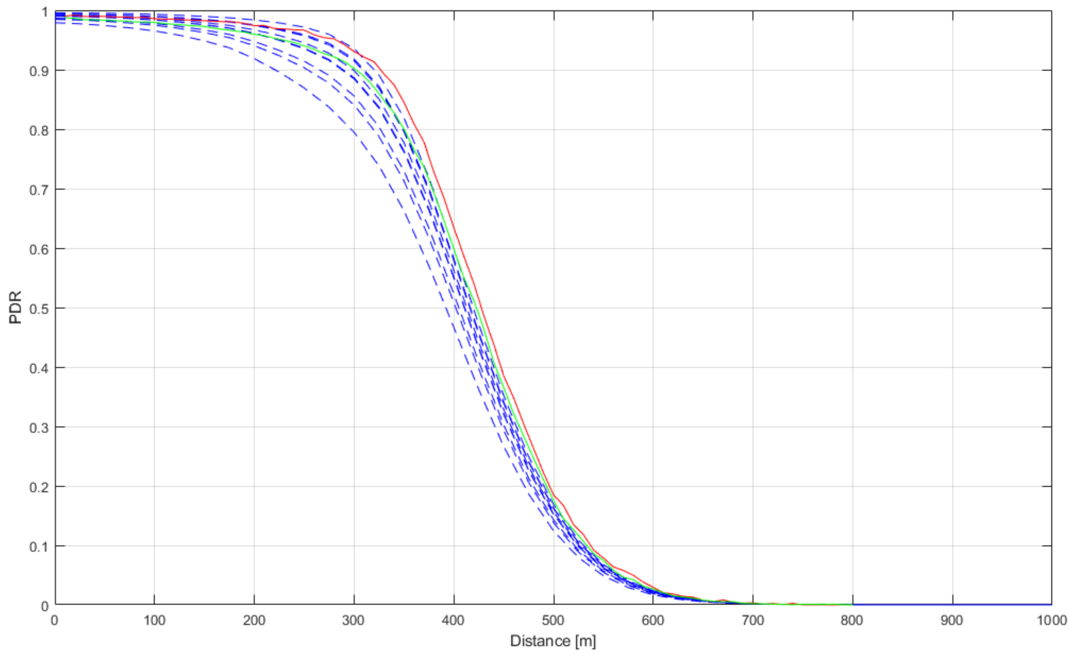


Figure 11: Packet Delivery Ratio (PDR) for different traffic mixes as a function of communication distance.

Figure 11 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 Use Case 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 Use Case 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 12.

Table 6: Location of RSUs in Use Case 3.1.

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

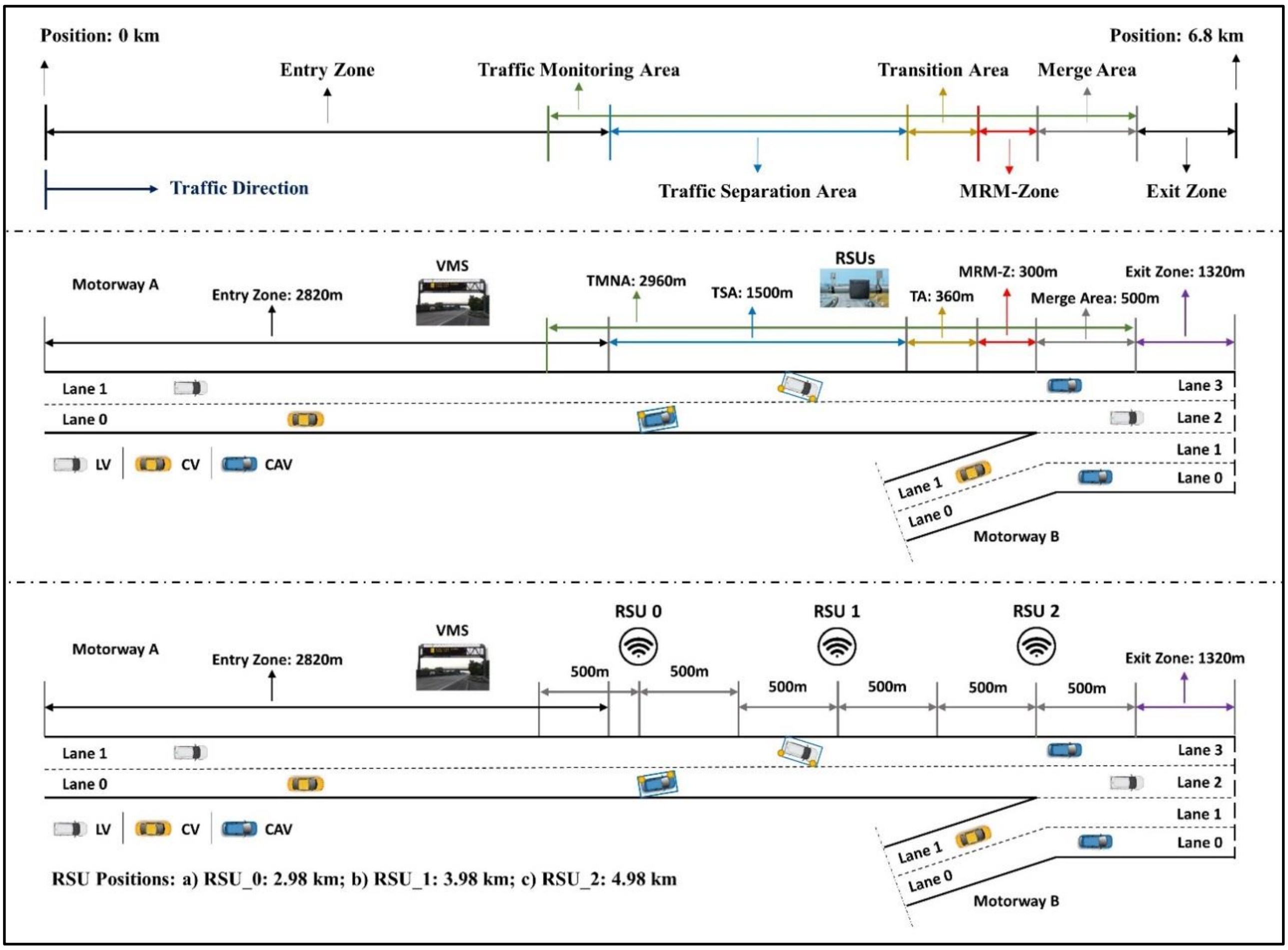


Figure 12: Schematic representation of Use Case 3.1.

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 13):

- 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.

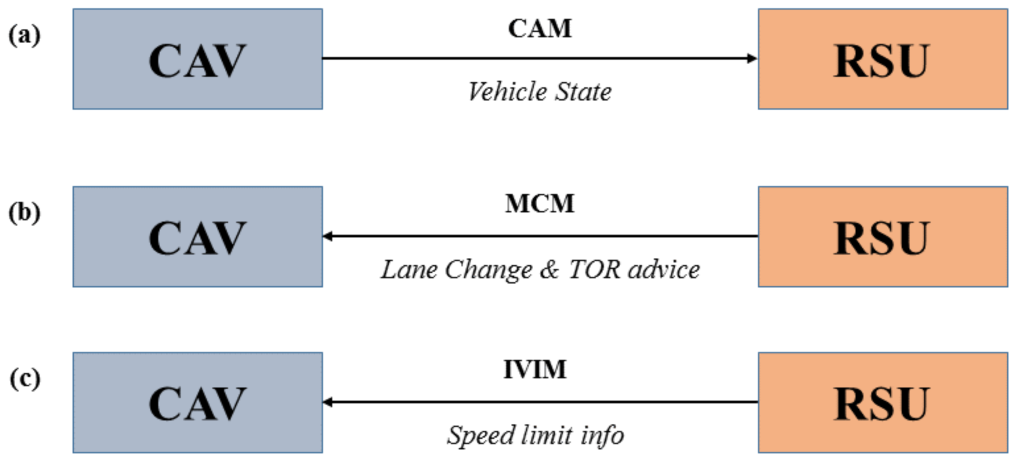


Figure 13: Communications in Use Case 3.3.

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 manoeuvre 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 present simulation results (traffic and communication KPIs) obtained for this use case. 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.

In the first project iteration, we solely presented 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) were quite computationally intensive and could not be completed by the time of submission of the first version of Deliverable D6.2 due to additional technical hindrances.

Use Case 3.1 requires substantially higher computational effort to simulate V2X communications as a result of significantly increased traffic demand compared to the other use cases. The exact requirements in computational time regarding each parameter combination examined in Use Case 3.1 when using ns-3 are listed in Table 7 (first iteration iTETRIS simulation runs). It can be observed that computational effort increases exponentially towards higher traffic demand levels.

In general, 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.

Table 7: Computational requirements of Use Case 3.1 simulations of 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 (first iteration iTETRIS simulation runs). A significant reduction of computational time can be observed due to the use of the LightComm module (simplified communication) in comparison with the use of the ns-3 simulator (realistic communication).

Table 8: Computational requirements of Use Case 3.1 simulations 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

Significant improvements were made with respect to the runtime efficiency of Service 3 application source code in the second project iteration. Thus, it was made possible to efficiently run LOS A and LOS B iTETRIS simulations with the use of the ns-3 simulator (simulation errors were eliminated and debugging was simplified and expedited). Despite the improvements in runtime efficiency, substantial issues were still encountered with LOS C simulations which could not be eventually run with success. As aforementioned, runtime hugely escalates with increasing number of vehicles input during the simulation runtime. Moreover, it was identified that congested traffic conditions were evolving during LOS C simulations. Hence, the total number of transmitted messages per simulation step remarkably increased as well. The latter factors render LOS C simulations very slow, memory consuming, and error-prone.

For example, in the case of LOS C – Mix 1 (lowest number of CAVs in the fleet mix/lesser number of messages transmitted), a single simulation run/seed required more than 45 GB of RAM to be run. Considering that each node on the server has 120 GB of RAM and that two nodes were available, it is evident that at most two simulation seeds could be run on each node at a time. Running 4 LOS C

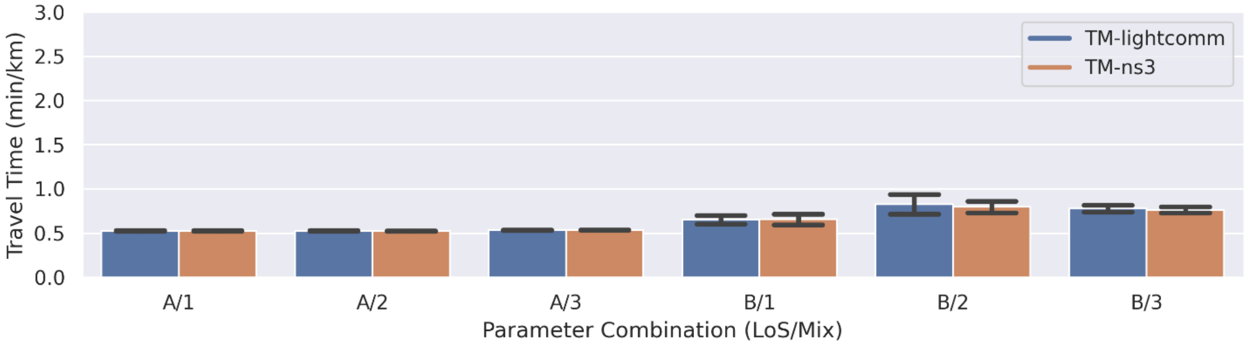
– Mix 1 simulation seeds on the server required several days and the simulations did not always finish successfully. It was estimated that for the case of LOS C – Mix 3 simulations (highest number of CAVs in the fleet mix/highest number of messages transmitted), runtime would be in the range of multiple months. Thus, simulation results for LOS C with the ns-3 simulator are not available in the final version of Deliverable D6.2.

Traffic

Traffic efficiency is assessed based on average network statistics (travel time and throughput bar plots) and spatio-temporal plots 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 14 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. Thus, the simulation of realistic communication protocols did not adversely impact the efficacy of the simulated traffic management strategy.

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 15). This also supports the claim that the V2X communications do not impact the efficiency of the traffic management procedures for this use case in urban traffic conditions.



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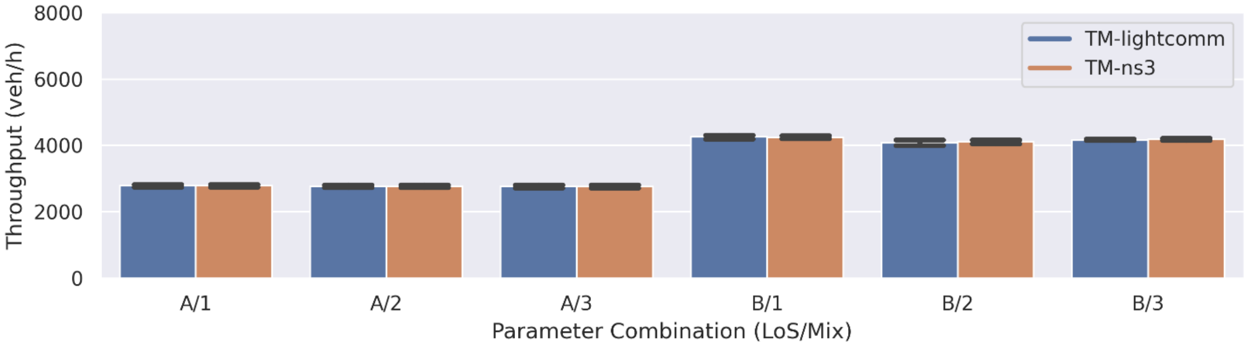

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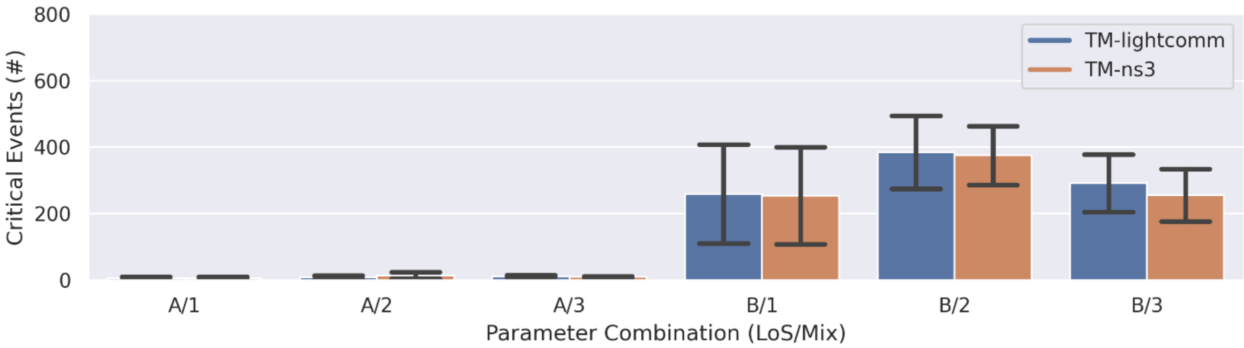

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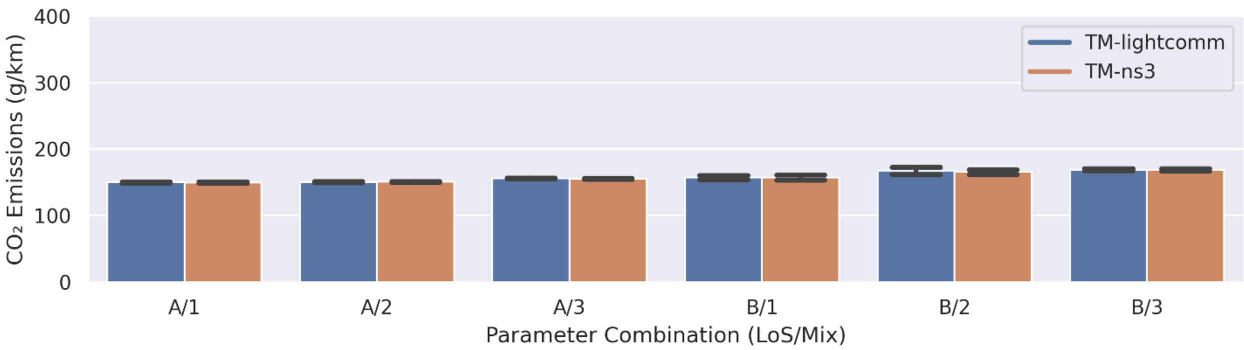
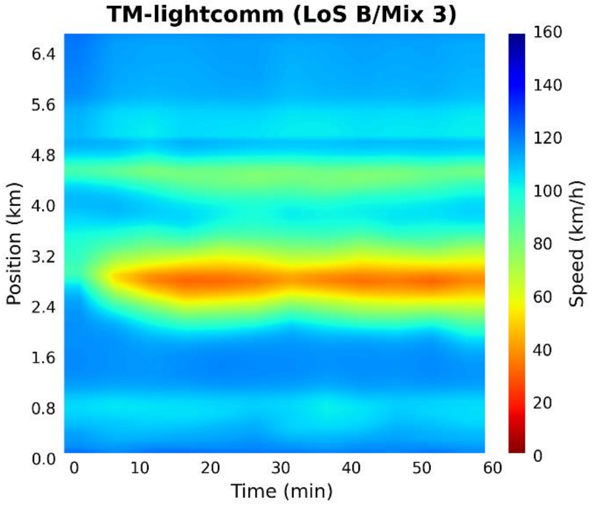
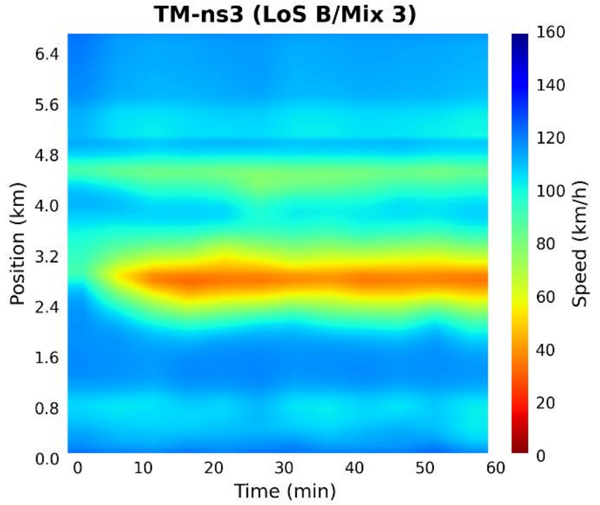


(d)

Figure 14: Simulation results (average network statistics) for Use Case 3.1. Error bars show the standard deviation among ten replications over one-hour simulation time for the corresponding parameter combination.



(a)



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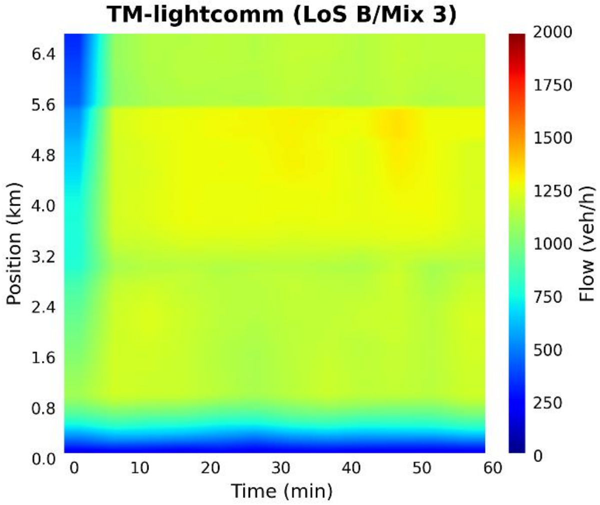

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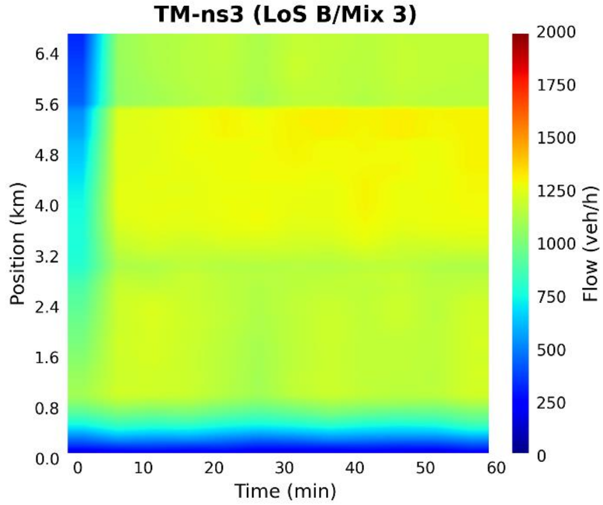


(d)

Figure 15: Average spatio-temporal plots for measured speeds (upper row) and flows (bottom row) for Use Case 3.1.

Communication

This section analyses the impact of the traffic management measures in the performance of V2X communications LOS A and LOS B scenarios. First, we analyse the congestion level of the V2X communications channel through the Channel Busy Ratio (CBR) metric. The CBR is defined as the percentage of time that the channel is sensed as busy. Table 9 shows the average CBR for all the vehicles in the simulation. The results are reported for combinations of use case parameters, i.e. levels of service (LOS A and B) and traffic mixes (1, 2, 3). The obtained results show that the maximum channel load is achieved for LOS B and traffic mix 3 which is around 25 % and other configurations achieves very low CBR. This means that on average the V2X communications channel is only sensed as busy by the vehicles for 25 % of the time. These channel load levels are considered adequate for the deployment of the traffic management measures implemented for this

TransAID Use Case 3.1. Congestion control protocols that reduce the channel load to prevent channel congestion would only be activated at higher channel load levels (e.g., beyond 60 % CBR). This indicates that the interference level caused by the messages transmitted by the RSUs and the connected vehicles is low, and a relatively low number of packets will be lost due to packet collisions.

Table 9: Channel Busy Ratios for Use Case 3.1.

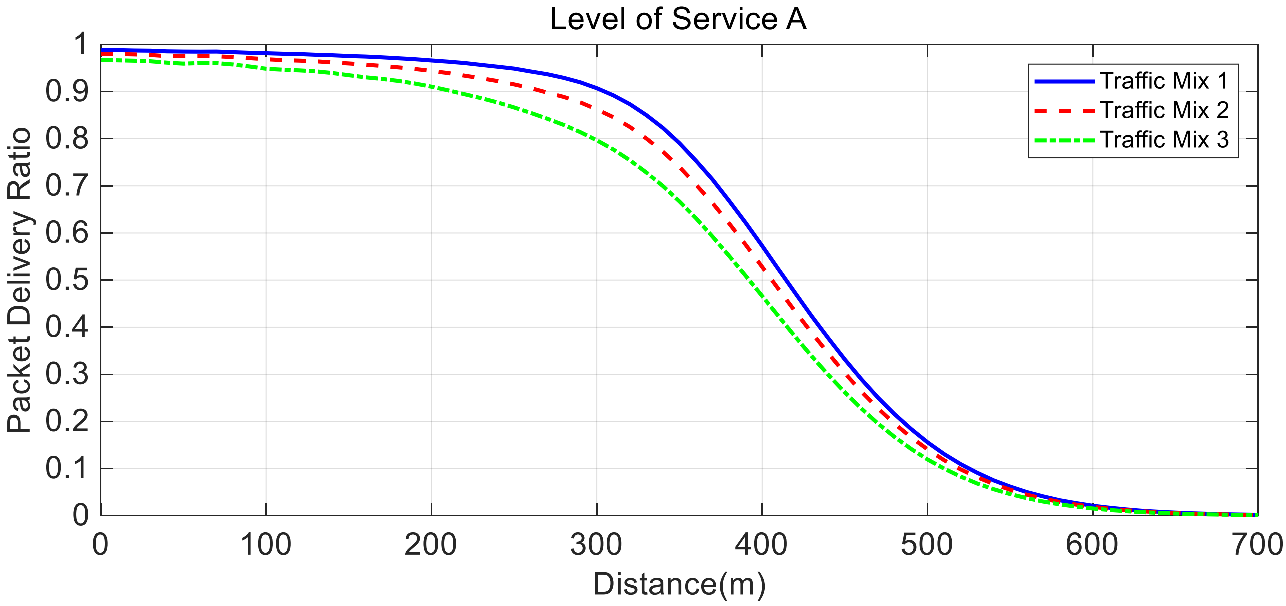
	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS A	6.19 %	9.61 %	14.43 %
LOS B	10.41 %	18.63 %	25.88 %

The observed low percentage of CBR will significantly increase the successful reception of packets and reduce the latency. Table 10 shows the average latency of the V2X communications performed during the simulations of Use Case 3.1. 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 levels of service (LOS A and B) and traffic mixes (1, 2, 3) is around or below 1.5 ms. These significant lower latency values guarantee that the vehicles will receive the traffic management measures with enough time to safely execute the required manoeuvres. Also, the observed latency values match with the existing ones available in the literature for relatively low CBR levels [16].

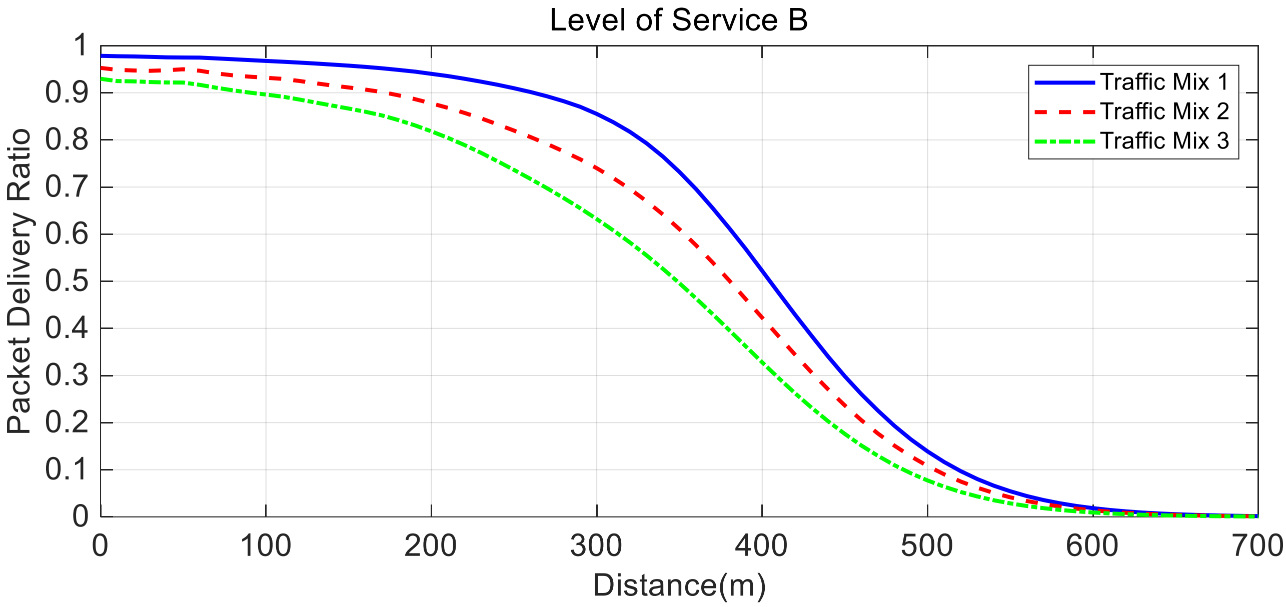
Table 10: Latencies for Use Case 3.1.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS A	0.76 ms	0.83 ms	0.95 ms
LOS B	0.81 ms	1.08 ms	1.46 ms

Finally, Figure 16 shows the PDR for the levels of service (LOS A and B) with different traffic mixes. 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 16 also includes the results obtained for different traffic mixes in order to analyse the effects of increasing the number of CVs and CAVs in the use case. As expected, increasing the number of vehicles with V2X capabilities in the use case 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 use case, the traffic results reported above show that the V2X communications do not negatively impact the traffic KPIs. This is the case because vehicles can start receiving messages at distances beyond 500m, although with low probability. The results obtained show that, in the worst-case scenario (LOS B and traffic mix 3), a PDR higher than 0.9 can be achieved at distances up to 100 m. This distance is increased to 200 m for LOS A for the same traffic mix. Also, due to the deployment of multiple RSUs, the probability of receiving the packet at short distances increases significantly. Therefore, the probability that at least one traffic related message is received before reaching 300m is very high, even in the scenario with LOS B and traffic mix 3, despite the reported low PDR.



(a)



(b)

Figure 16: Packet Delivery Ratio for Use Case 3.1.

The overall analysis of the communications KPIs shows that the reliability of the V2X communications is in principle sufficient to satisfy the communication needs of the traffic management measures of Use Case 3.1.

3.3.3 Discussion

The results obtained from the iTETRIS simulations, that encompassed both ideal and realistic communications, were found to be similar with the corresponding results (no communications) of Deliverable 4.2 [2] for LOS A and B. Thus, the conducted analysis has shown that the transmission of the necessary messages to execute the traffic management measures of the TransAID Service 3 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 use case, 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**
    - Lane change/keep and ToC advice is received by virtually all CAVs to ensure increased efficiency and safety levels at the motorway merge area. However, it should be noted that immediate and complete compliance of CAVs with RSU advice 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 use case. The current implementation takes this into account which adds to the robustness of the traffic management algorithm.

d) **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.
    - 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.

3.4 Use Case 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 use case 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 use case (see Figure 17) 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.

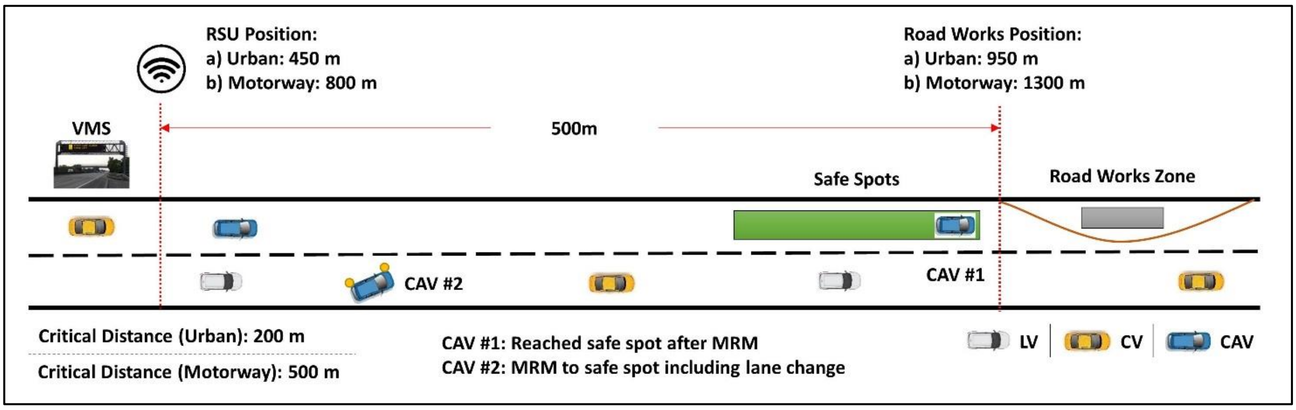


Figure 17: Schematic representation of Use Case 4.2.

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 18):

- 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.

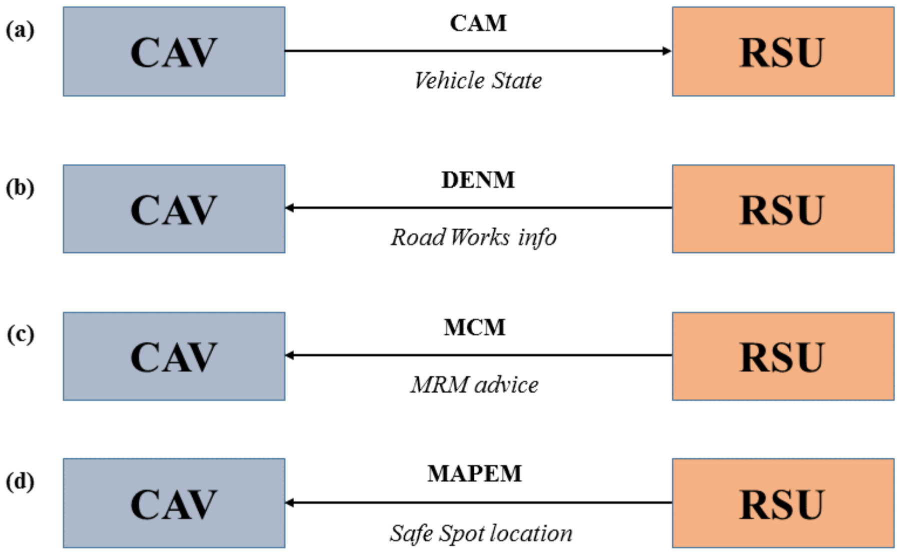


Figure 18: Communications in Use Case 4.2.

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 use case (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 use case parameters (demand level and vehicle mix) for ideal and realistic communications as described in Section 2.2.

Traffic

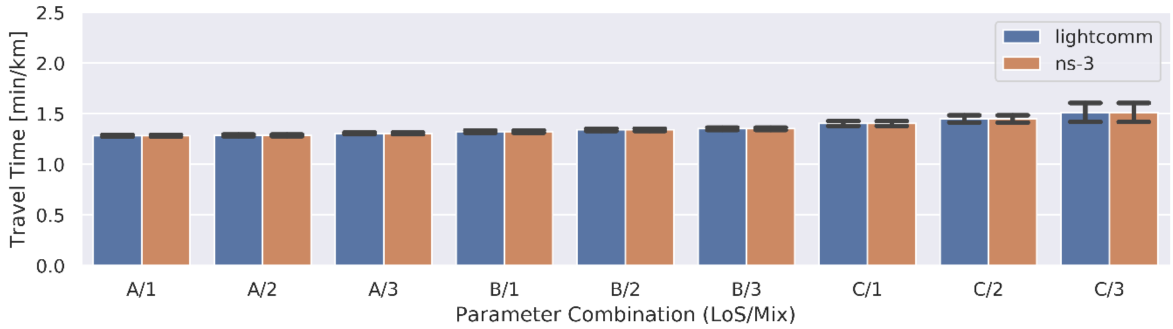
Traffic efficiency is assessed based on average network statistics (travel time and throughput bar plots) and spatio-temporal plots of speed and flow (obtained from simulated detector raw output). On the contrary, traffic safety and environmental impacts are assessed explicitly based on network-wide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

Figure 19 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 20). This supports the claim that the V2X communications do not impact the efficiency of the traffic management procedures for this use case in urban traffic conditions. Moreover, it is noted that the simulation results related to the urban scenario and presented in Figure 19 and Figure 20 are similar to those included in [2] where V2X communications were not considered in the simulation experiments.

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 21). 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 plots 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 22 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 23). 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).



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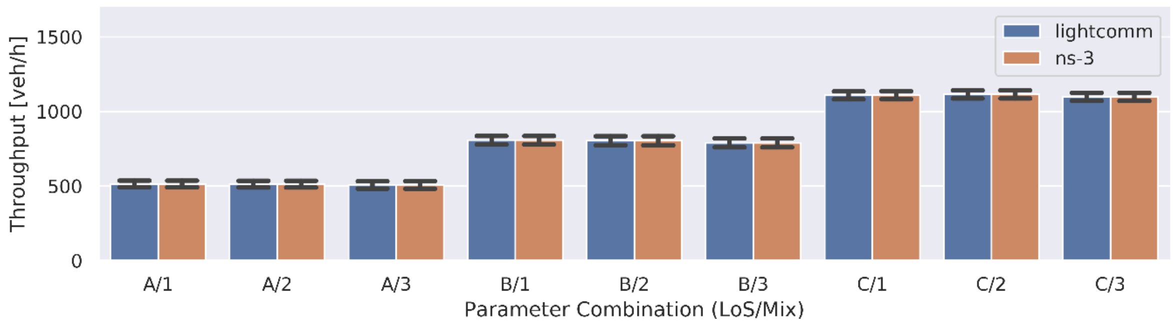

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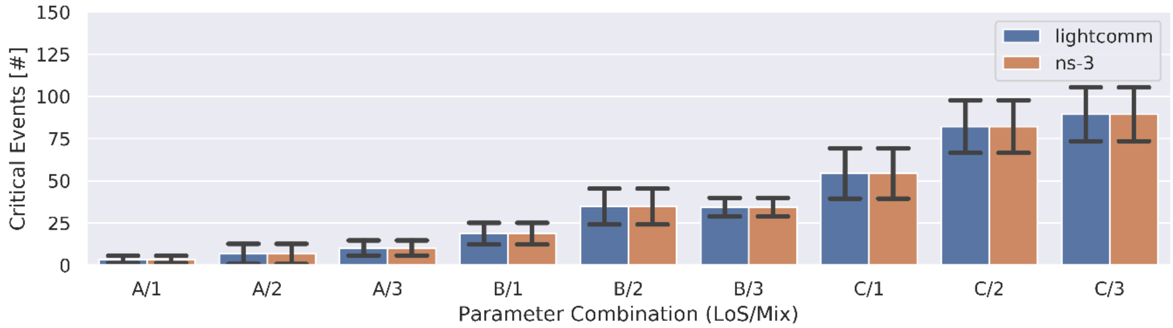

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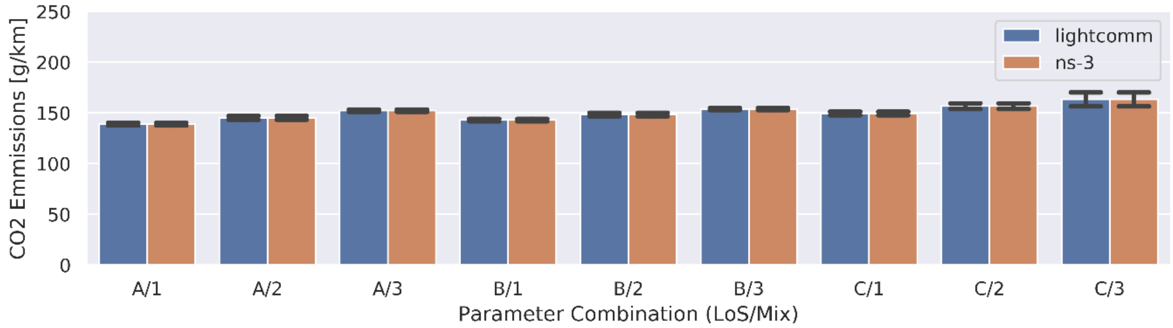


(d)

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

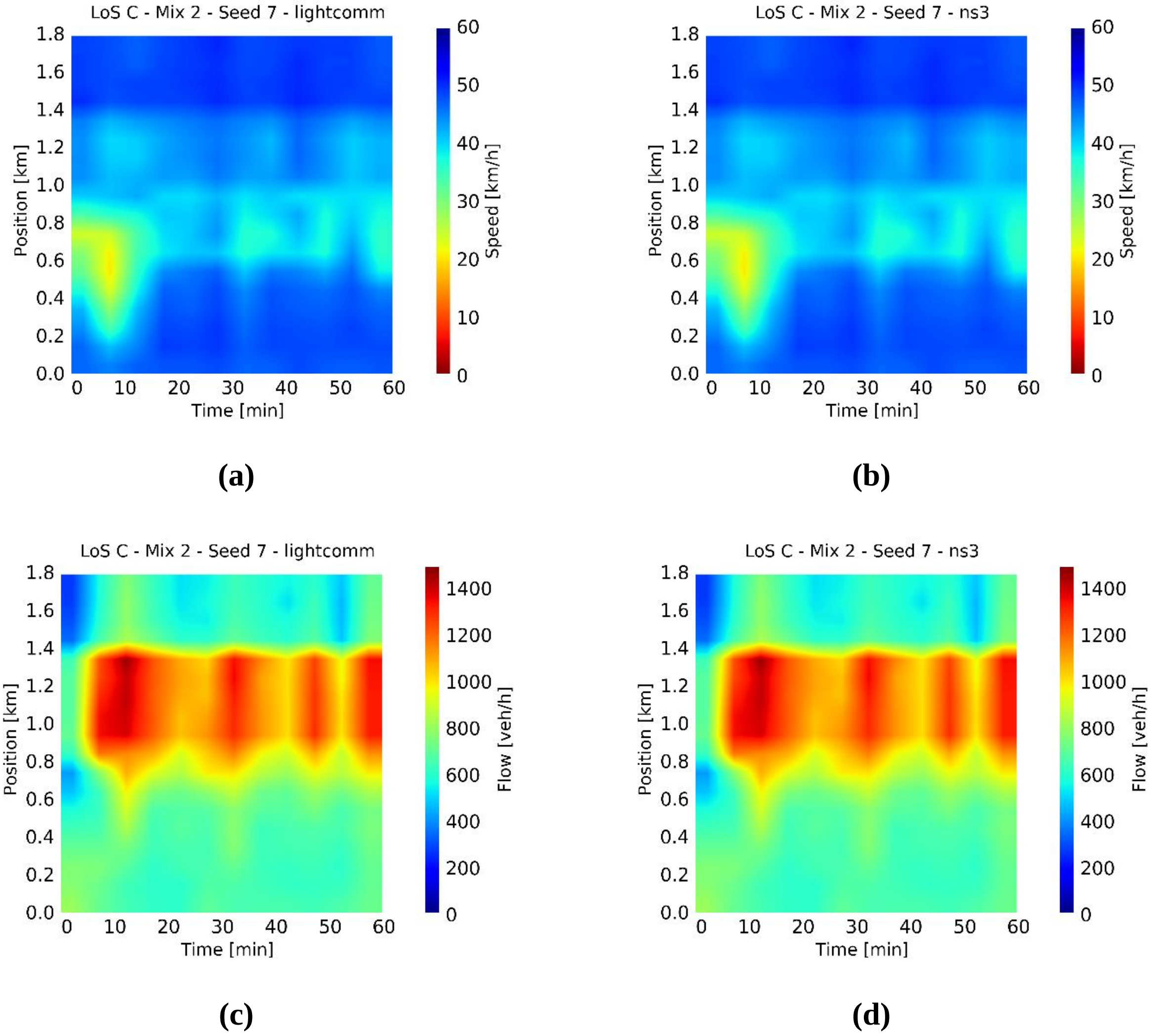
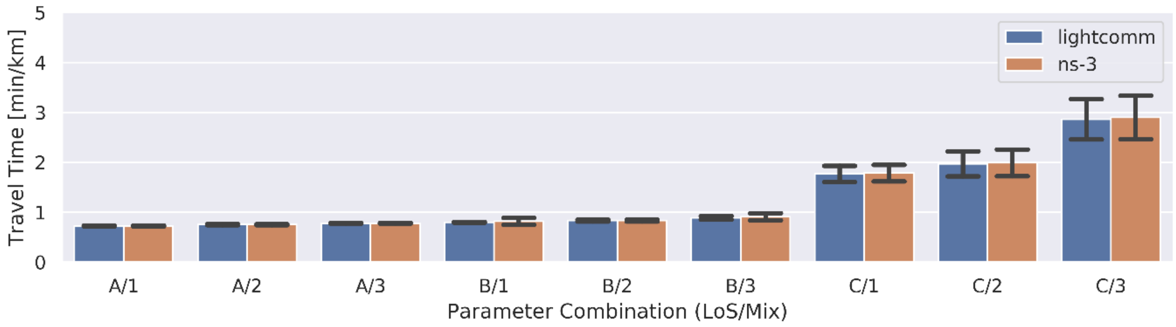
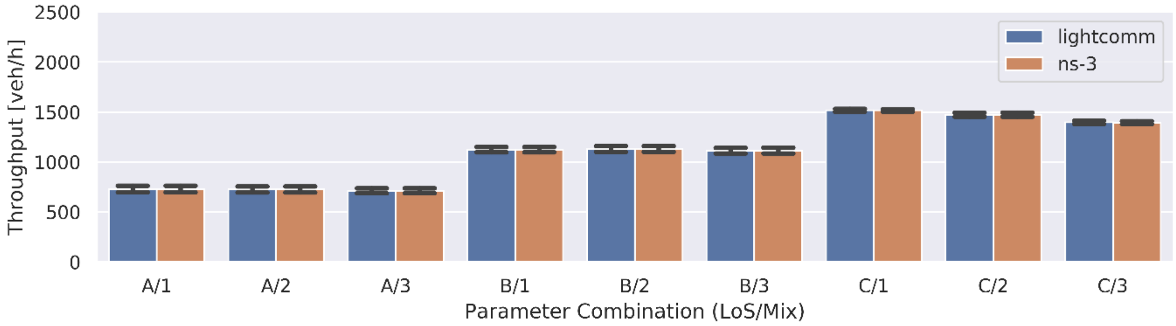


Figure 20: Example spatio-temporal plots for measured speeds (upper row) and flows (bottom row) for Use Case 4.2 (urban network, LOS C, vehicle mix 2, seed 7). The left column corresponds to ideal communications and the right column to realistic communications.



(a)



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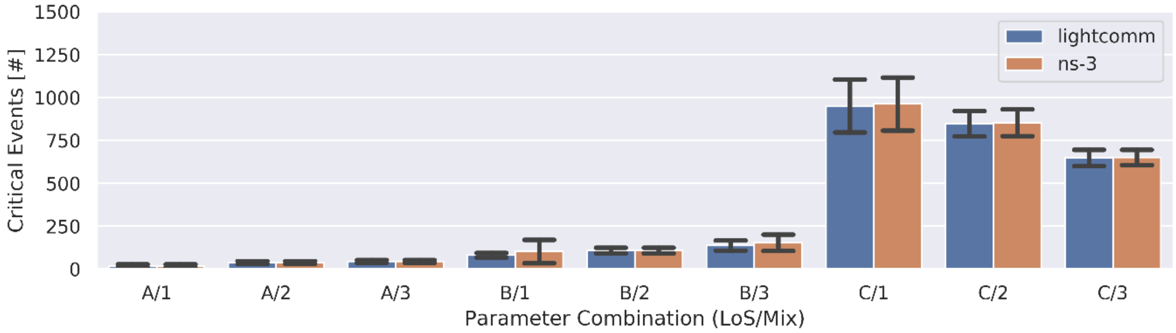

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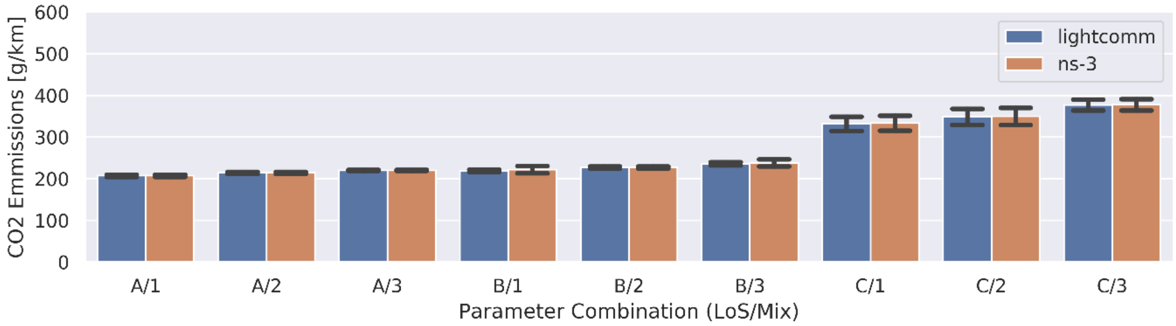
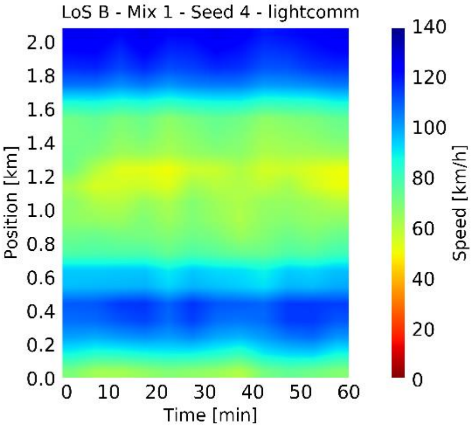
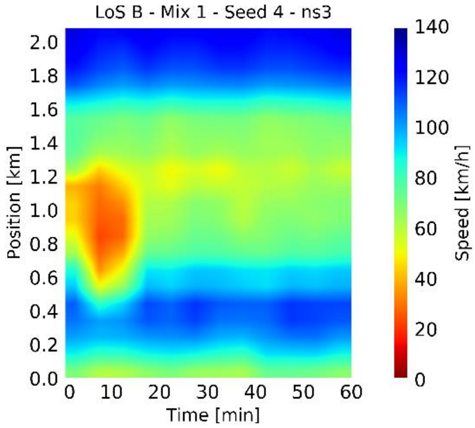


(d)

Figure 21: Simulation results (average network statistics) for Use Case 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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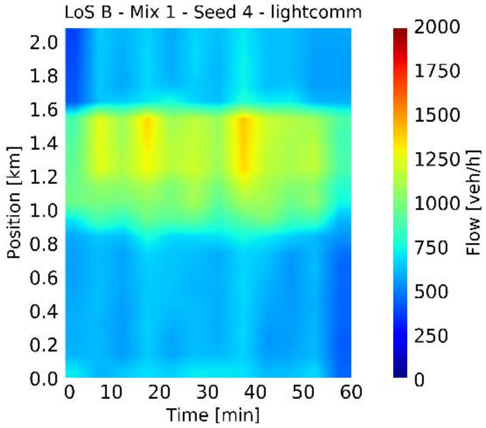

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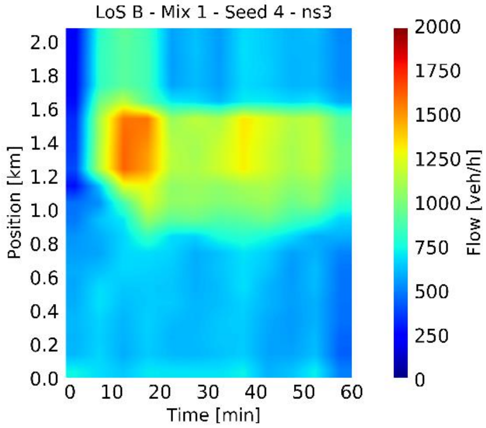


(d)

Figure 22: Example spatio-temporal plots for measured speeds (upper row) and flows (bottom row) for Use Case 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.

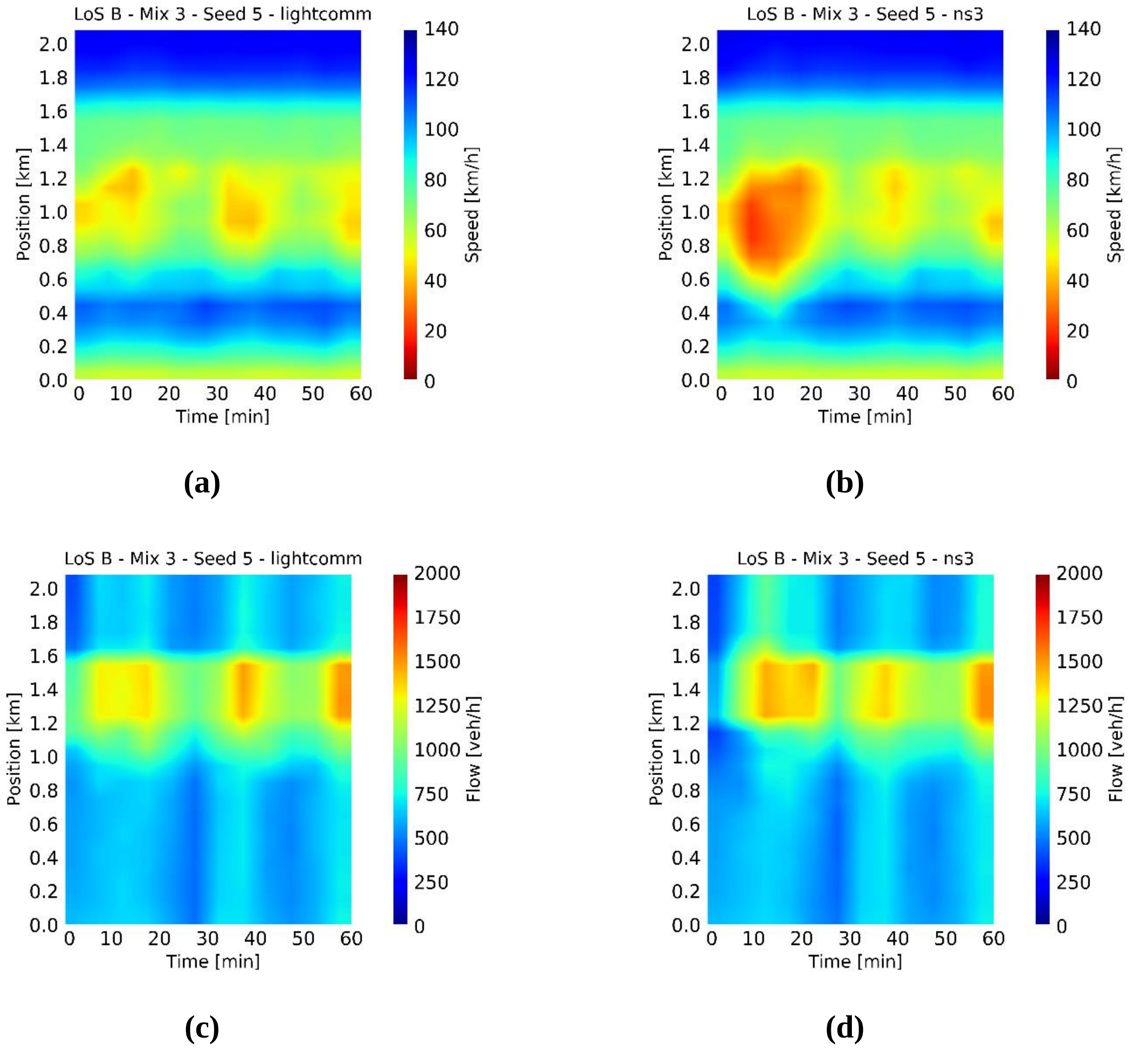


Figure 23: Example spatio-temporal plots for measured speeds (upper row) and flows (bottom row) for Use Case 4.2 (motorway network, LOS B, vehicle mix 3, seed 5). The left column corresponds to ideal communications and the right column to realistic communications.

Communication

This section evaluates the impact of the traffic management measures of Use Case 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 use case. Table 11 summarises the CBR for the different levels of service (LOS) and traffic mixes evaluated in the urban scenario of Use Case 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 Use Case 4.2 are not generating an excessive V2X communications load that could congest the communications channel in the urban scenario.

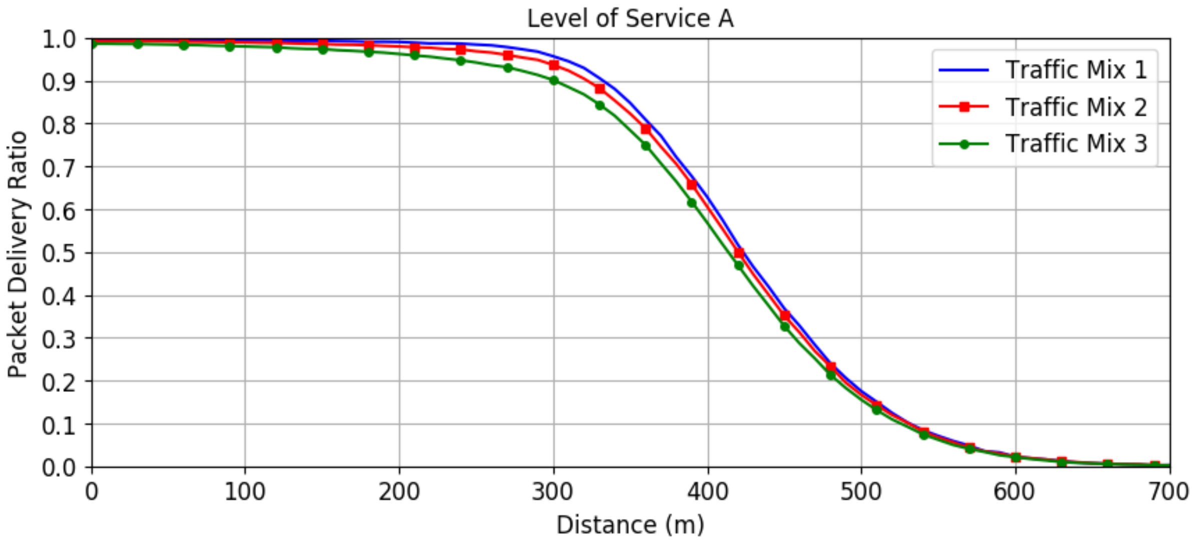
Table 11: Channel Busy Ratios for Use Case 4.2 in urban scenario.

	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 %

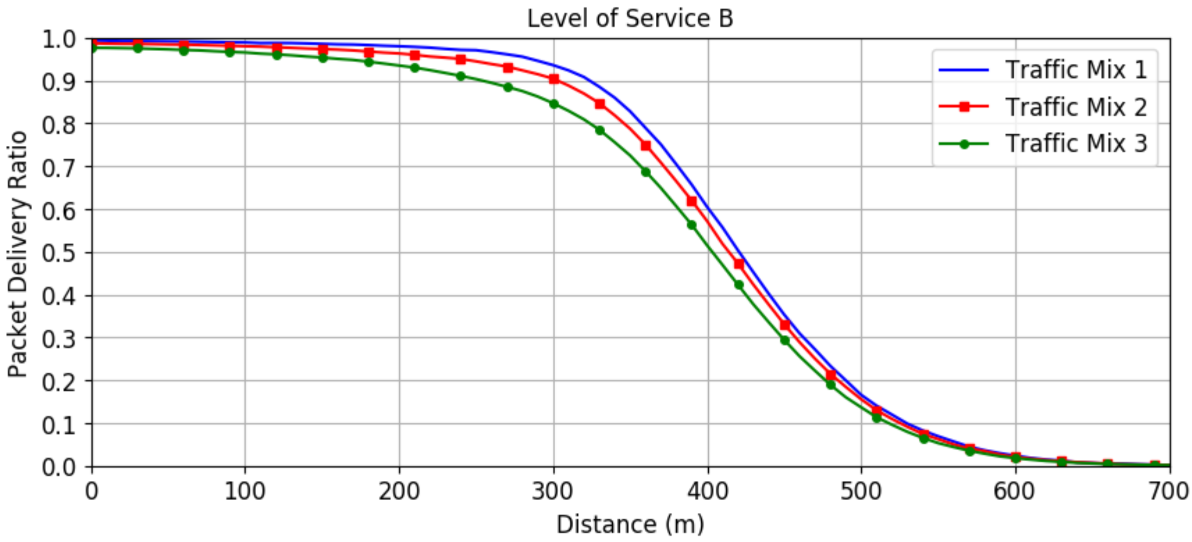
Table 12: Latencies for Use Case 4.2 in urban scenario.

	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 12 shows the average latency measured in the urban scenario of Use Case 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 12 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 Use Case 4.2.



(a)



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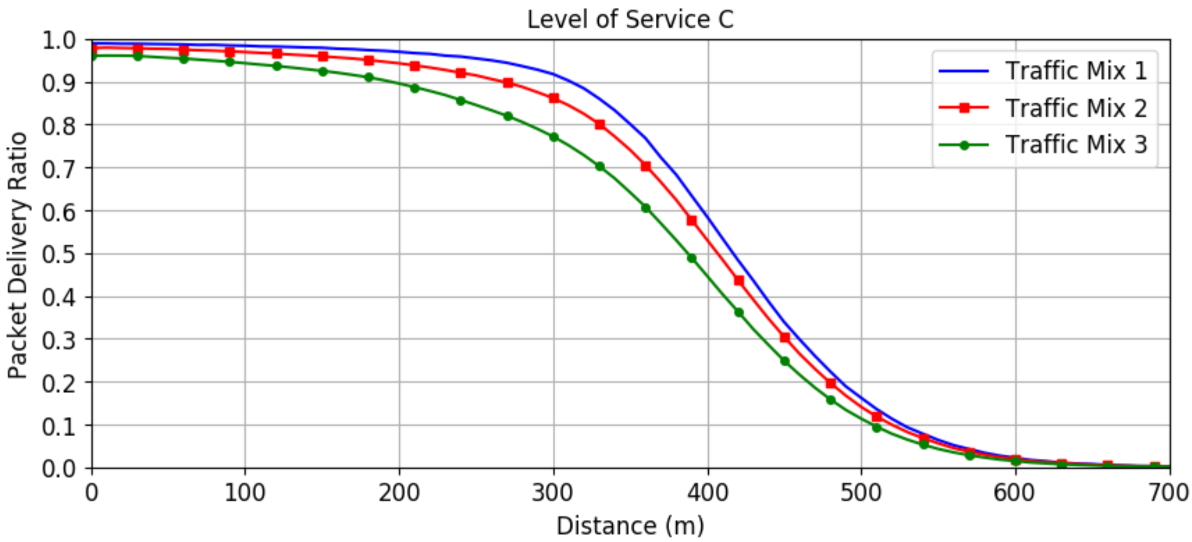


(c)

Figure 24: Packet Delivery Ratio for Use Case 4.2 in urban scenario.

Figure 24 shows the Packet Delivery Ratio (PDR) of the different levels of services and traffic mixes evaluated in the urban scenario of Use Case 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 24 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 Use Case 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 13 summarises the CBR for the different levels of service and traffic mixes evaluated in the motorway scenario of Use Case 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 13 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.

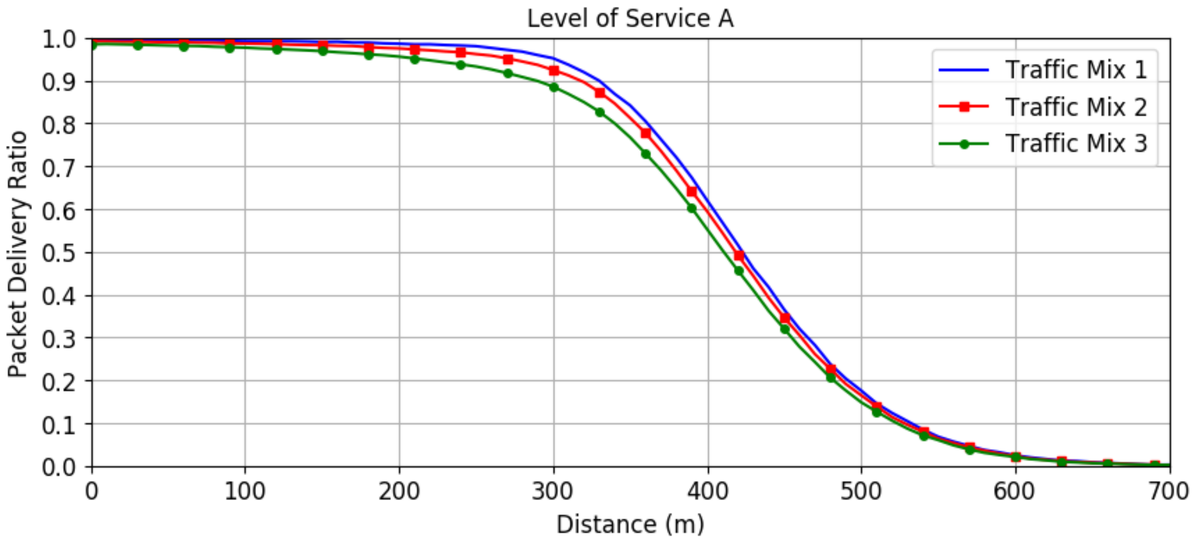
Table 13: Channel Busy Ratio for Use Case 4.2 in motorway scenario.

	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

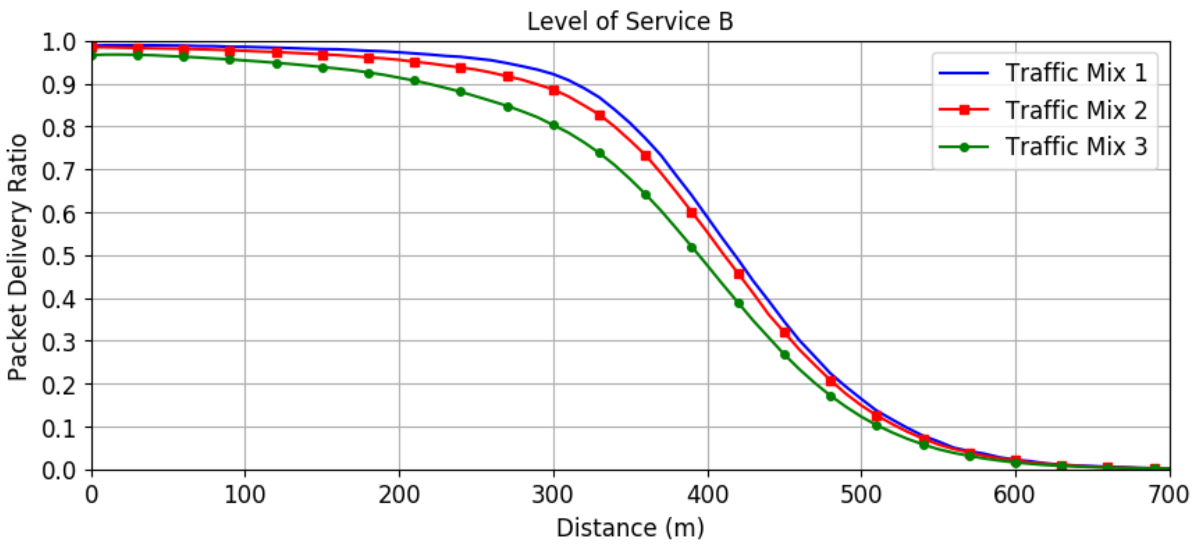
Table 14: Latencies for Use Case 4.2 in motorway scenario.

	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

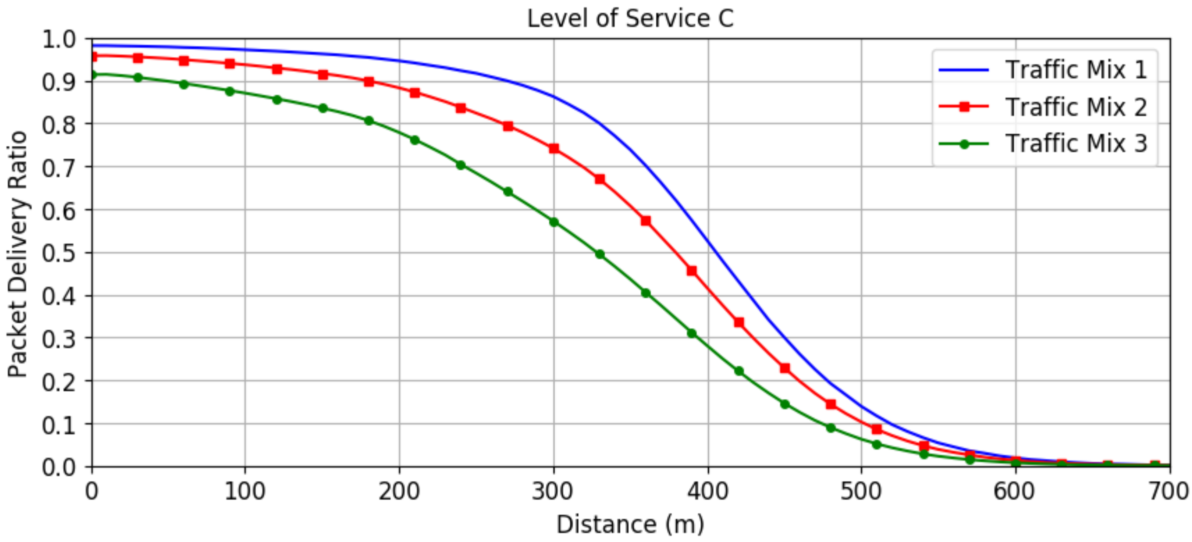
Table 14 shows the average latency of all the messages transmitted during the simulation time for the different parameter configuration of traffic mixes and levels of service. The reduced latency values obtained from the simulations show that V2X communications are not impeding the efficient and timely execution of the traffic management measures defined by Use Case 4.2, as vehicles have enough time to receive message and execute the corresponding manoeuvre in a safe and efficient way.


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

(b)



(c)

Figure 25: Packet Delivery Ratio for Use Case 4.2 in motorway scenario.

Figure 25 shows the PDR obtained in the simulation of the motorway scenario of Use Case 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 Use Case 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.

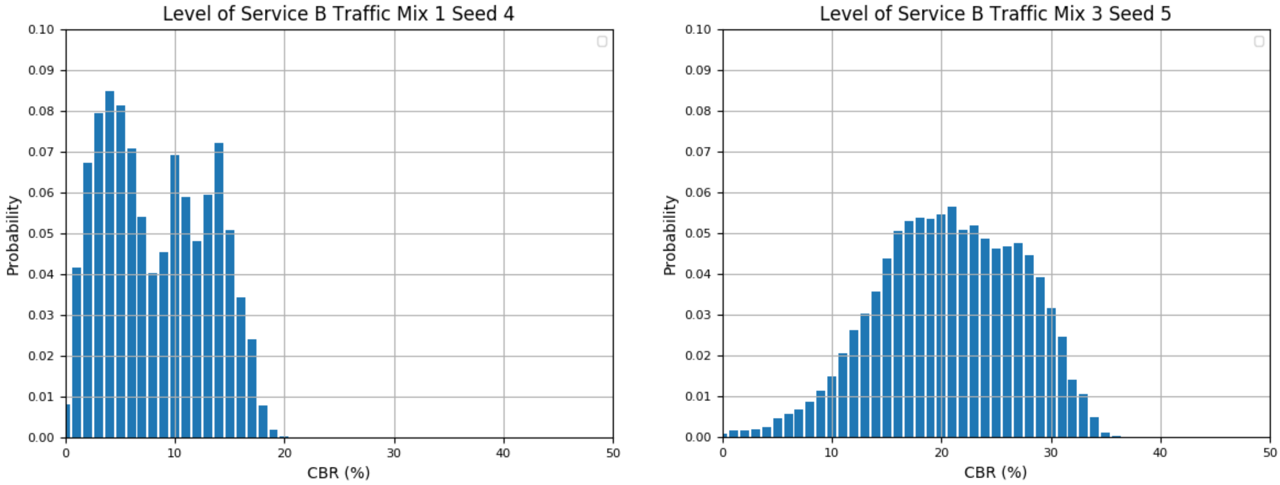


Figure 26: Channel Busy Ratio for the Use Case 4.2 in the motorway scenario. The left column shows the CBR for LOS B, Mix 1, Seed 4 and the right column shows the CBR for LOS B, Mix 3, Seed 5.

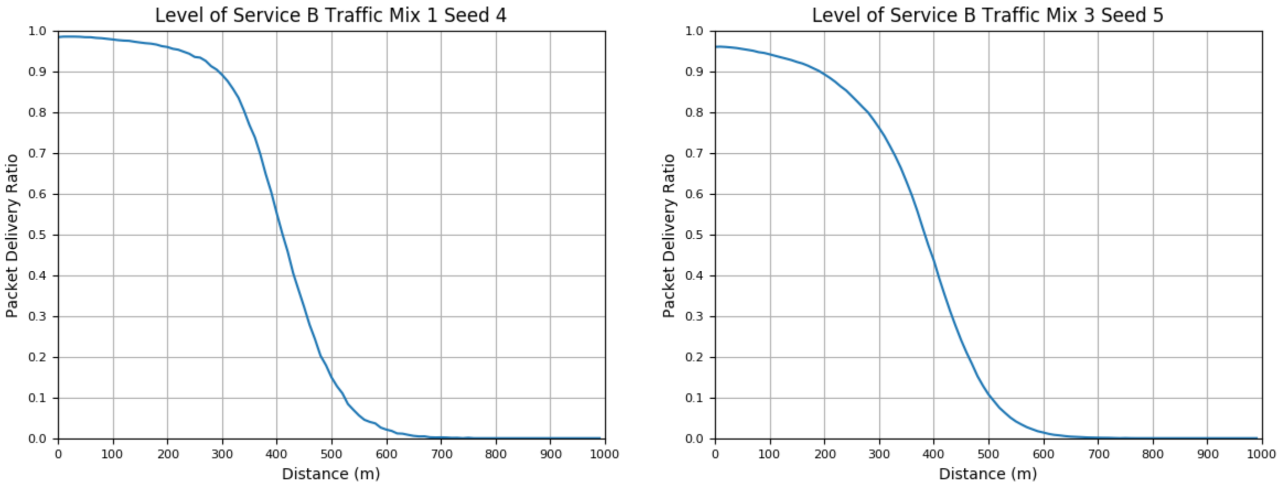


Figure 27: Packet Delivery Ratio for the Use Case 4.2 in the motorway scenario. The left column shows the PDR for LOS B, Mix 1, Seed 4 and the right columns shows the PDR for LOS B, Mix 3, Seed 5.

Figure 26 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 26 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 27 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 25. 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 use case, 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 Use Case 5.1: Schedule ToCs before No-AD zone

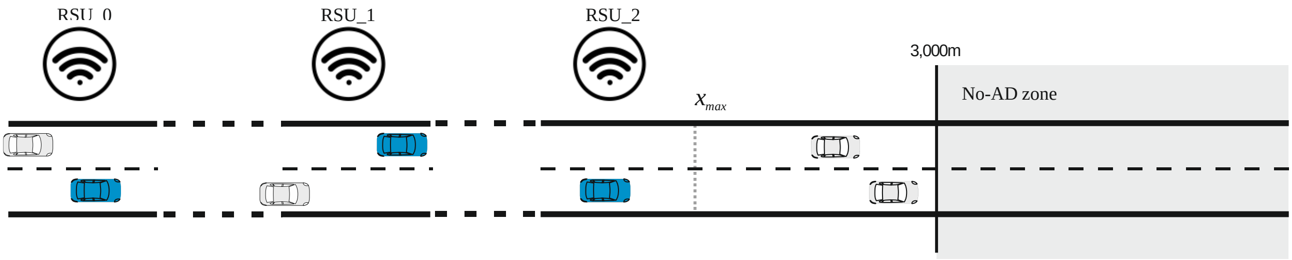


Figure 28: Schematic representation of Use Case 5.1.

3.5.1 Introduction

In this use case, 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 use case 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 28). Their locations are given in Table 15.

Table 15: Location of RSUs in Use Case 5.1.

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 use case 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.

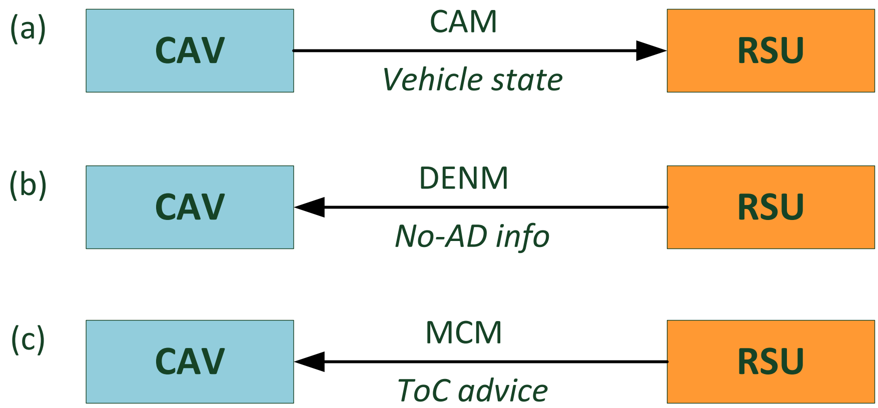


Figure 29: Communications in Use Case 5.1.

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 29.

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.

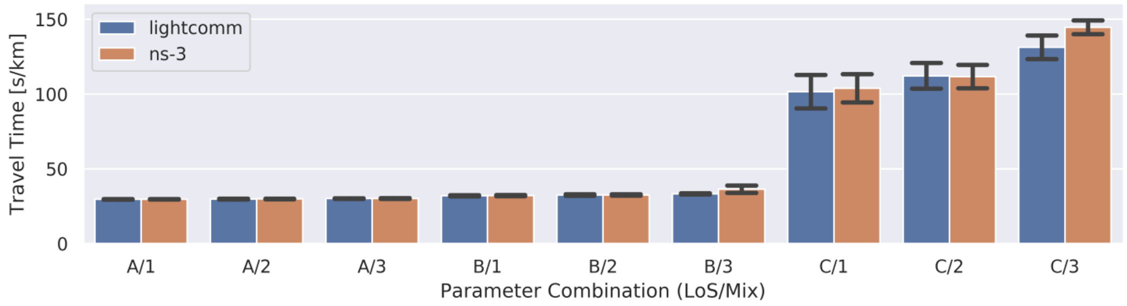
If a CAV receives a No-AD info, it will, *in any case*, take out a transition before entering the No-AD zone, regardless of whether a subsequent ToC advice was received. We assume that only the reception of a ToC advice may cause the vehicle to induce a transition earlier than the latest possible point x_{max} for starting a transition autonomously (see Figure 28), 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

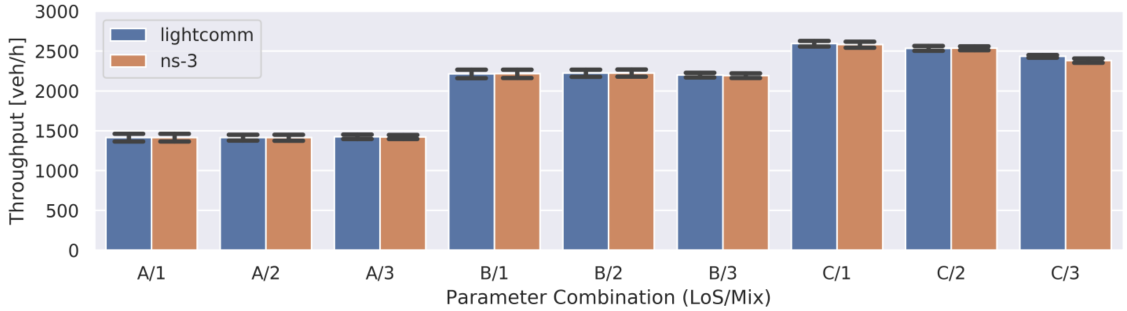
In this section, we present and describe the simulation results obtained for this use case. The main objective of the performance evaluation is to inspect the robustness of the TM procedures with respect to the simulation of realistic V2X data communication. To this end, we simulated all combinations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

Traffic

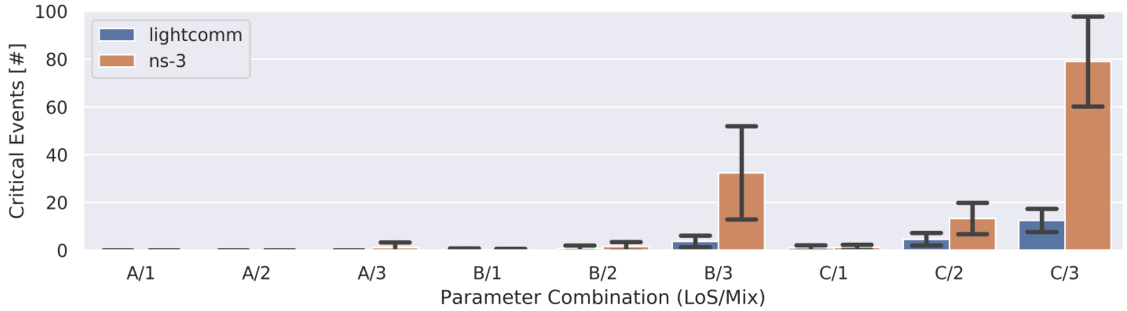
As in Deliverable 4.2 [2], we inspected the performance aspects traffic efficiency, traffic safety, and environmental impact, quantified with the network-wide traffic KPIs “travel time” and “throughput”, “critical events”, and “CO_2 emissions”, respectively (cf. [14]). Additionally, we inspected the 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)

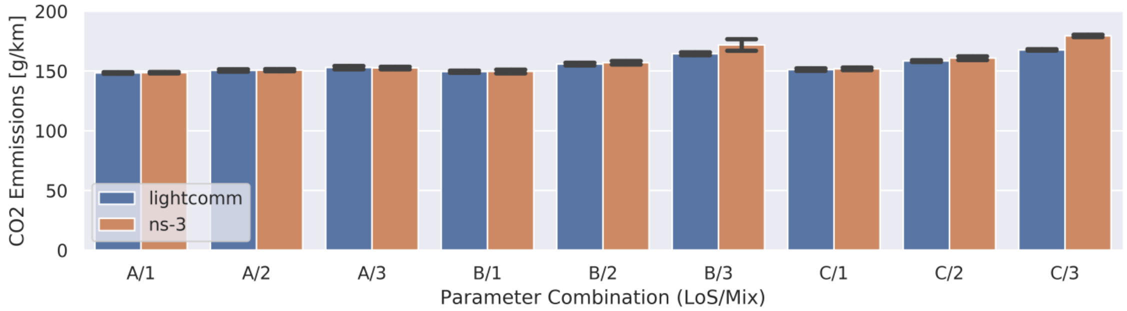
(a)


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)

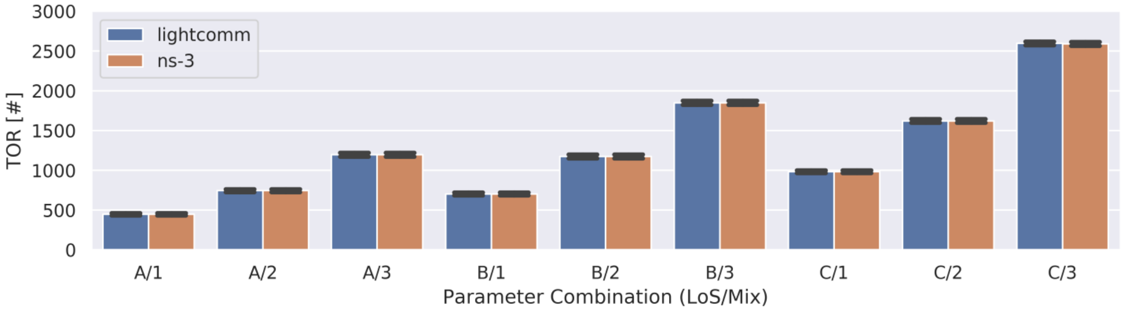
(b)


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)

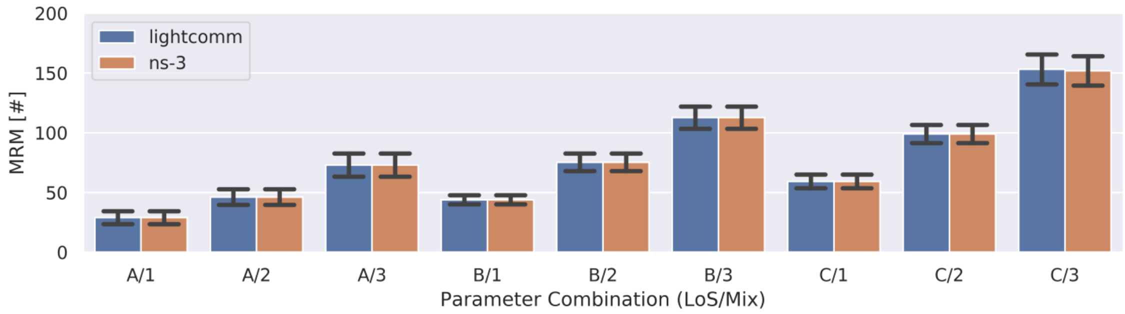
(c)


lightcomm
ns-3
CO2 Emmissions [g/km]
200
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)

(d)



(e)



(f)

Figure 30: Network-wide simulation results for Use Case 5.1. Error bars show the standard deviation among ten replications over one hour simulation time for the corresponding parameter combination.

Figure 30 summarises the obtained network-wide simulation results for this use case. 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 30 (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 30 (c), increases with the level of service but is still negligible in the case of ideal communication (LightComm). Furthermore, CO_2 emissions (see Figure 30 (d)) exhibit no notable differences across levels of service and increase only marginally with higher penetration rate. The travel times shown in Figure 30 (a) suggest that the use case 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 30 (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 use case (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 use case.

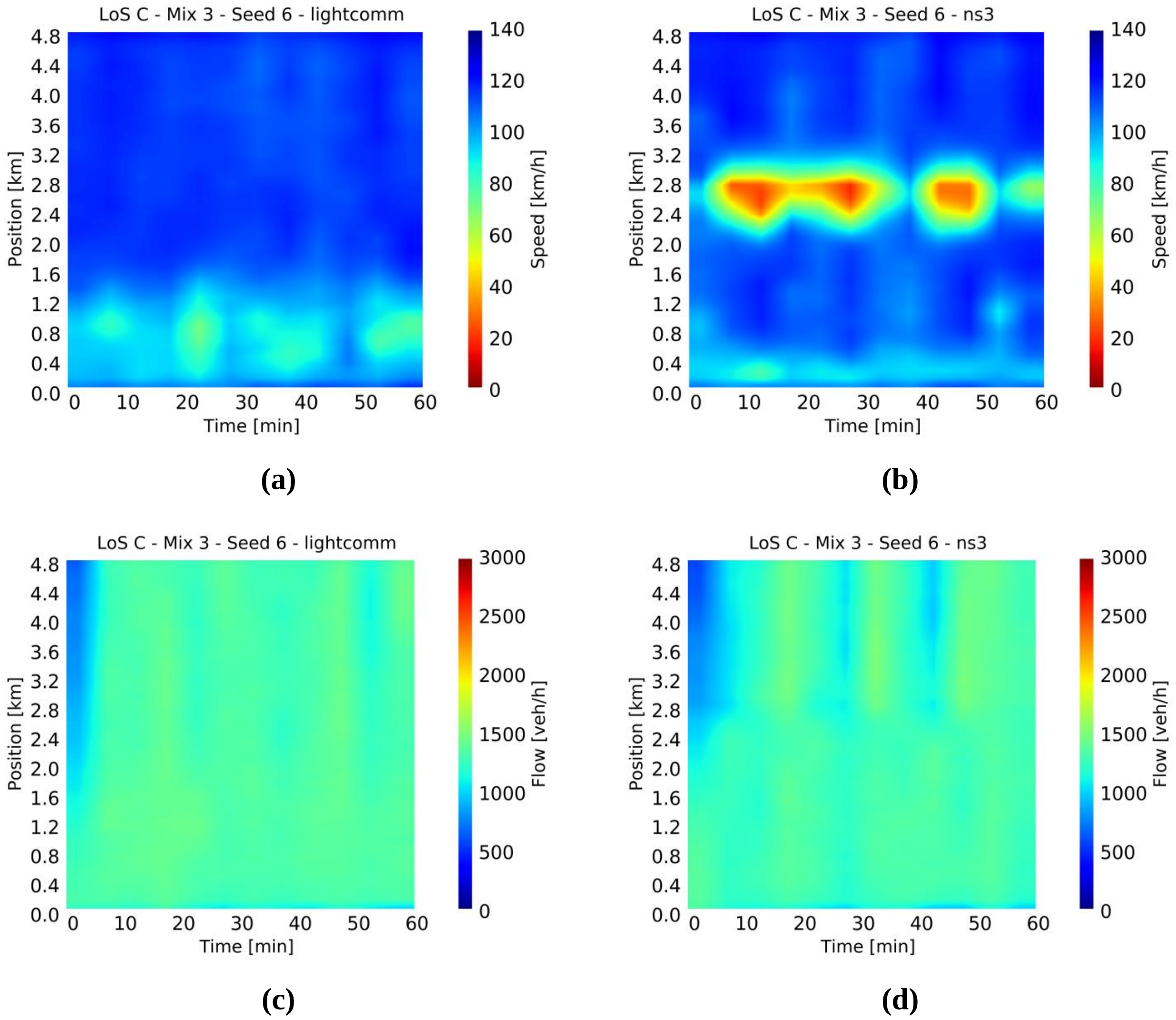


Figure 31: Exemplary spatio-temporal plots visualising KPIs speed (a, b) and flow (c, d), respectively, for Use Case 5.1. For both KPIs, ideal (a, c) and realistic (b, d) communication results are shown side-to-side for easier comparison.

A comparison of the results for ideal (LightComm) and realistic (ns-3) communication most prominently shows a significant impact on critical events (Figure 30 (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 30 (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 31: speeds just before the entry to the No-AD zone (at 3.0 km) are impaired when considering realistic communication (compare Figure 31 (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 16 shows the average CBR sensed by all the vehicles in the simulation for all combinations of use case 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 30 (a)), does not produce a similar increase in the CBR. This is the case because the generation rules of V2X messages (see Section 2.2.1) 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.

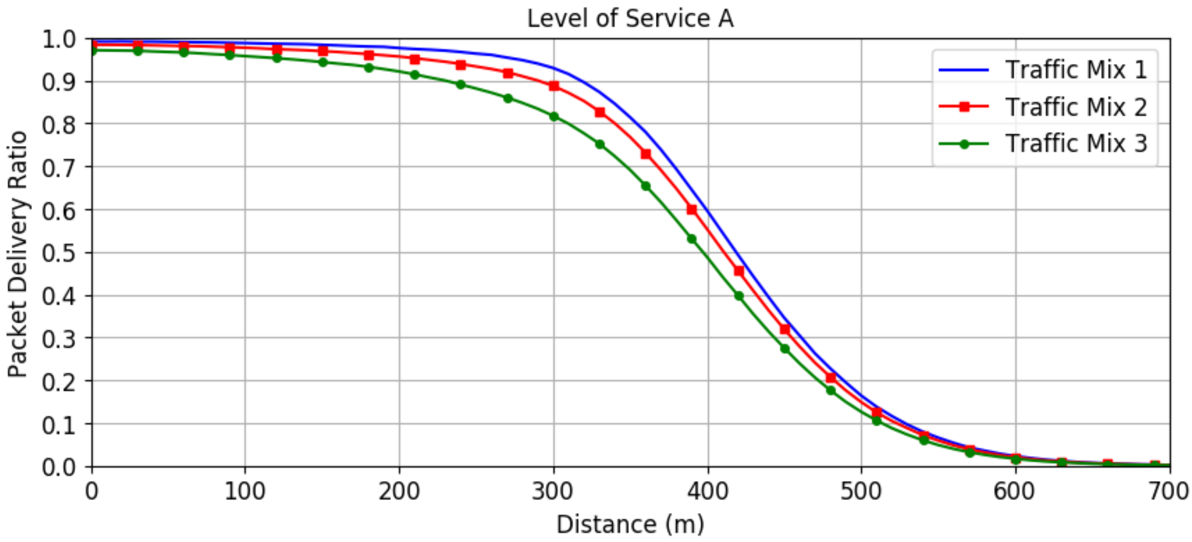
Table 16: Channel Busy Ratios for Use Case 5.1.

	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 %

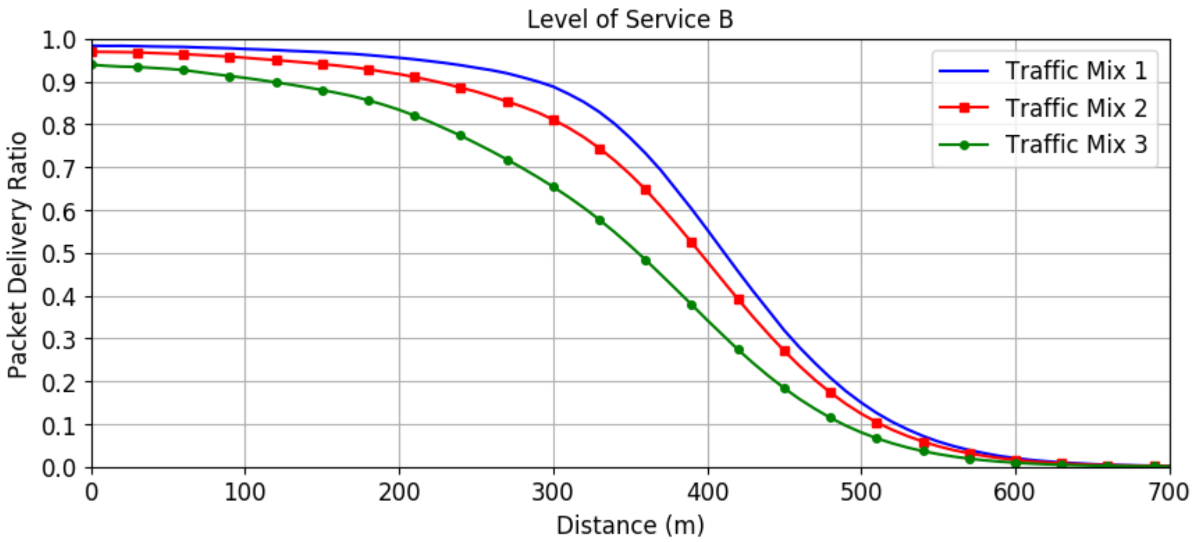
Table 17: Latencies for Use Case 5.1.

	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

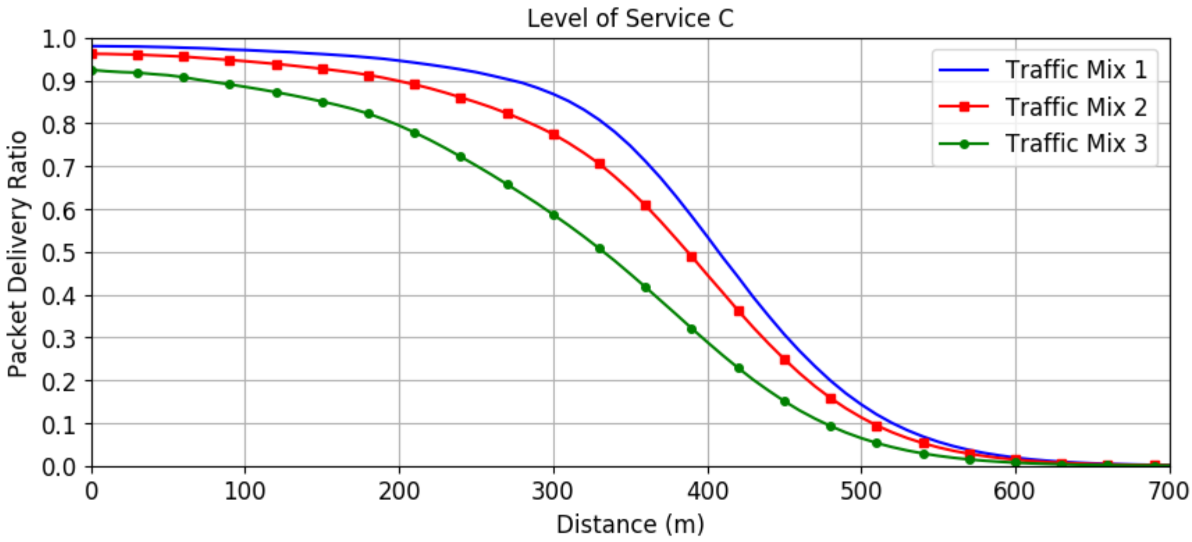
Table 12 shows the average latency of all transmitted messages in the simulation. The latency is computed as the time elapsed since the generation of the packet in the ITS Facility layer to the reception of the packet at the receiver side. The short latency measured in the simulations for all combinations of use case 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

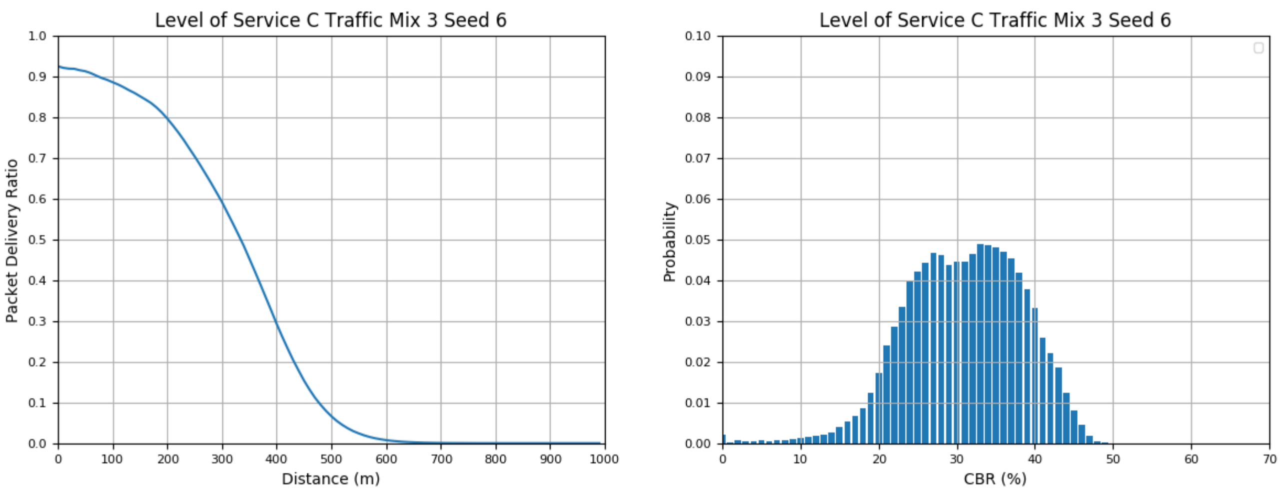
(b)



(c)

Figure 32: Packet Delivery Ratio of Use Case 5.1.

The PDR for the different combinations of use case parameters of the simulations of Use Case 5.1 is shown in Figure 32. 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 use case parameters that produced the traffic disturbance (LOS C, Mix 3, Seed 6) in terms of V2X communications.



(a) **(b)**

Figure 33: Packet Delivery Ratio (left) and Channel Busy Ratio (right) of Use Case 5.1 for the parameter configuration LOS C, traffic mix 3 and seed 6.

Figure 33 shows the PDR as a function of the distance and the probability distribution function (PDF) of the CBR measured in Use Case 5.1 when LOS is set to C, Mix is 3 and the Seed is 6. The reported results in Figure 33 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 30, but simply some lost packet. As stated in the discussion of the traffic KPIs of Use Case 5.1, 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 use case 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 Use Case 5.1 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 use case, 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 use case. 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 use cases 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 use cases were ported to the iTETRIS platform where feasible (see Use Case 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 use cases 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 Use Cases 1.1 and 2.1 have shown that these use cases are not adversely impacted by realistic V2X communication. Furthermore, Use Case 4.2 exhibited no significant impact of realistic communication on traffic KPIs for both urban and motorway traffic cases. However, in the motorway traffic case, a few single simulation runs have shown a sensitivity of the traffic management algorithm (in its current state) to communication errors, which might increase and turn significant for higher traffic demands and/or penetration rates than the ones considered here. Similarly, traffic KPI results for Use Case 5.1 suggest a certain sensitivity of the proposed traffic management measures to realistic V2X communication. For both traffic management algorithms, the origin of this sensitivity was traced to single, non-repeated transmissions of some infrastructure advice messages, which were not correctly received due to errors during wireless signal propagation. These flaws can be fixed by employing a transmission mechanism that ensures the correct reception of these infrastructure advices.

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 LOS C simulations for Use Case 3.1 could not be successfully completed, despite the improvements in runtime efficiency for the implementation of Use Case 3.1.

In conclusion, the performance evaluation of the considered use cases 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 Use Case Simulations - Second Iteration

4.1 Use Case 1.3: Queue spillback at exit ramp

4.1.1 Introduction

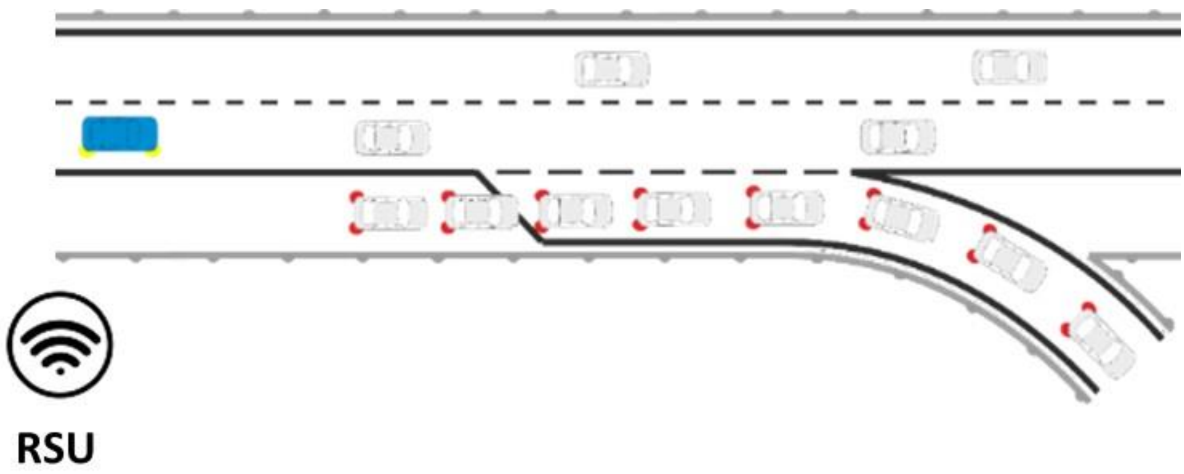


Figure 34: Schematic representation of Use Case 1.3.

Use Case 1.3 consists of a two-lane motorway and an exit ramp. Due to congestion downstream of the exit, a queue builds on the exit lane of the motorway. In order to improve traffic safety and increase traffic throughput, two measures are used by the traffic management system:

- The speed limit will gradually be decreased from the free-flow speed (120 km/h for passenger vehicles) upstream of the queue to 50 km/h in the section where the queue occurs.
- A section of the emergency lane is opened for traffic (for vehicles queuing to use the exit ramp).

(note that a more detailed description of the use case can be found in [12])

It is important that the same traffic rules apply for all vehicles, at all times. All vehicles without communication will base their information on VMSs along (or above) the motorway. Hence, changes in speed limits or access to the emergency lane apply from the same discrete locations, i.e. the location of the VMSs.

It is expected that CAVs will also be able to interpret many common traffic signs, including those regarding speed limits and open/closed traffic lanes. Therefore, even when communication fails, the behaviour of the CAVs will remain unchanged. The communication between the RSU and the vehicles merely serves as a confirmation of the information from the traffic signs.

Because the simulations for this use case do not show any impact of the communication efficiency on the traffic KPIs, we will only analyse the performance of the communication in the remainder of this section.

Vehicles broadcast their actual speed and position to other vehicles and to the RSU using MCM messages. The RSU communicates the state of the emergency lane and changes in speed limit to the vehicles using DENM messages.

It is assumed the RSU gets its information about the traffic density from detection loops, camera's, or other hardware. This information is not obtained from V2X communication. In the simulations, SUMO functions are used to gather this information from the traffic model environment, and are not derived from the MCM messages received by the RSU.

4.1.2 Results

Running the simulations took very long calculation times, especially for the higher LOSs. For LOS B, we obtained the following run times:

run_id	LOS		mix	seed	runtime
TD_1_TM_0_DB_FSP_seed_0	B	TD_1	0	0	13:56:27
TD_1_TM_0_DB_FSP_seed_1	B	TD_1	0	1	15:05:08
TD_1_TM_0_DB_FSP_seed_2	B	TD_1	0	2	13:54:29
TD_1_TM_0_DB_FSP_seed_3	B	TD_1	0	3	23:57:42
TD_1_TM_0_DB_FSP_seed_4	B	TD_1	0	4	15:30:07
TD_1_TM_1_DB_FSP_seed_0	B	TD_1	1	0	25:03:41
TD_1_TM_1_DB_FSP_seed_1	B	TD_1	1	1	28:06:40
TD_1_TM_1_DB_FSP_seed_2	B	TD_1	1	2	21:46:06
TD_1_TM_1_DB_FSP_seed_3	B	TD_1	1	3	25:49:07
TD_1_TM_1_DB_FSP_seed_4	B	TD_1	1	4	25:13:46
TD_1_TM_2_DB_FSP_seed_0	B	TD_1	2	0	62:23:25
TD_1_TM_2_DB_FSP_seed_1	B	TD_1	2	1	57:46:35
TD_1_TM_2_DB_FSP_seed_2	B	TD_1	2	2	60:15:07
TD_1_TM_2_DB_FSP_seed_3	B	TD_1	2	3	59:40:33
TD_1_TM_2_DB_FSP_seed_4	B	TD_1	2	4	56:39:28

The average calculation time was about 33 hours per seed. For LOS C, this was even worse:

run_id	LOS		mix	seed	runtime
TD_2_TM_0_DB_FSP_seed_3	C	TD_2	0	3	39:29:20
TD_2_TM_1_DB_FSP_seed_1	C	TD_2	1	1	71:11:34

Also, as the simulations worked with higher numbers of vehicles and the communications overhead increased, software crashes occurred frequently. For LOS D, this sometimes happened after 250 hours of simulation, which equates to over 10 days. A partial solution was to restart the crashed simulations each time, given that there was a chance they would succeed.

Due to the previously mentioned very long calculation times for this use case, the frequent crashes, and the limited relevance of communication on traffic performance, the number of simulations was limited to 5 seeds for every vehicle mix for LOS B, 2 seeds for every vehicle mix for LOS C, and no simulations for LOS D (instead of 10 seeds in other use cases).

Traffic

As explained in the introduction above, in this use case the traffic KPIs are independent of the quality of the communication.

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. The CBR is defined as the percentage of time that the channel is sensed as busy. Table 18 shows the average CBR for all the vehicles in the simulation. The results are reported for all combinations of use case parameters, i.e. levels of service (LOS B and C) and traffic mixes (1, 2, and 3). The obtained results show that for all the combinations of use case parameters, the CBR is around or below 35 % (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 34 % of the time. These channel load levels are considered adequate for the deployment of the traffic management measures implemented for this use case. Congestion control protocols that reduce the channel load to prevent channel congestion would only be activated at higher channel load levels. This indicates that the interference level is low and a relatively low number of packets will be lost due to collision.

Table 18: Channel Busy Ratios for Use Case 1.3.

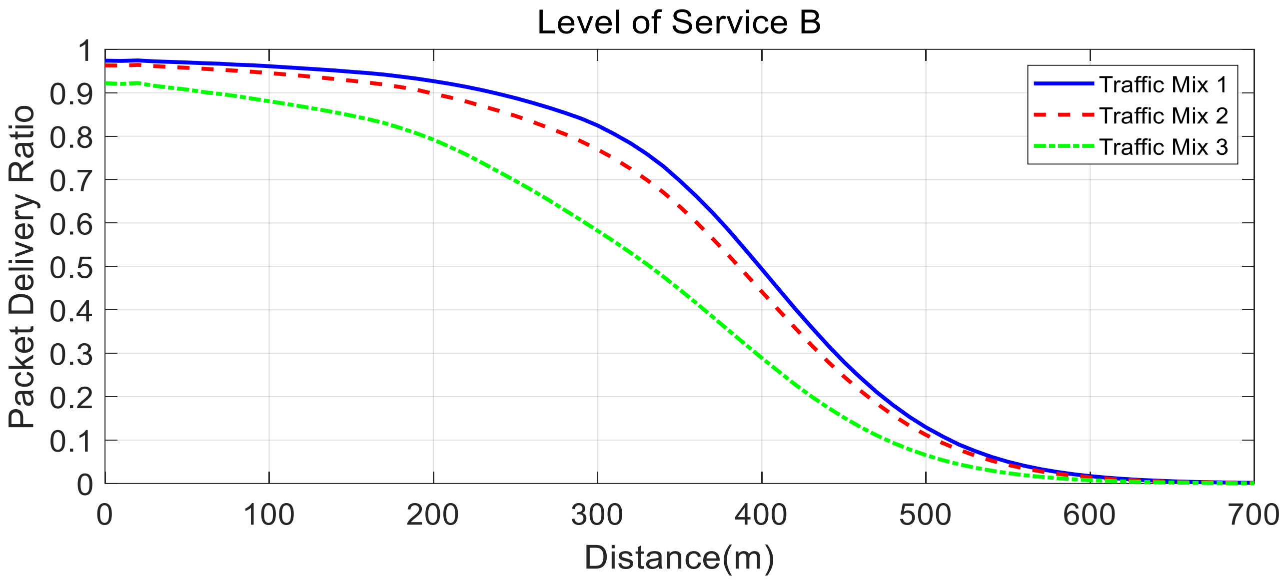
	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	11.7 %	16.0 %	26.7 %
LOS C	15.5 %	21.6 %	34.9 %

The observed low percentage of CBR will improve the successful reception of packets and reduce the latency. Table 19 shows the average latency of the V2X communications performed during the simulations of Use Case 1.3. 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 use case parameters is around or below 2.5 ms. These significant lower latency values guarantee that the vehicles will receive the traffic management measures with enough time to safely execute the required manoeuvres. Also, the observed latency values match with the existing ones available in the literature for relatively low CBR levels [16].

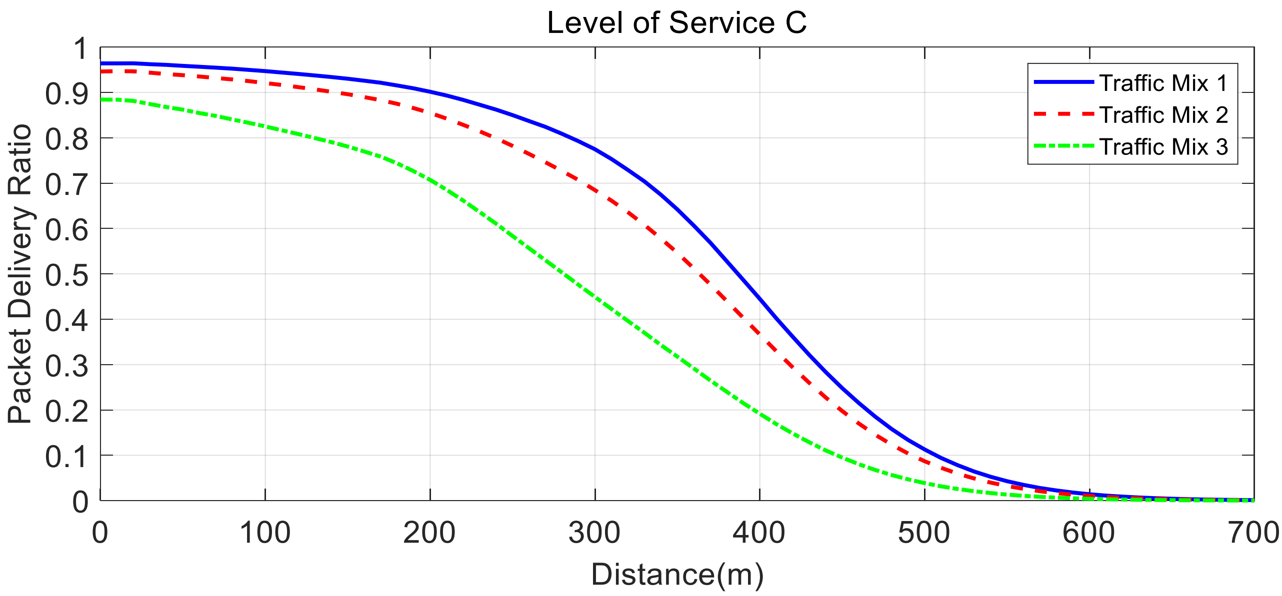
Table 19: Latencies for Use Case 1.3.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	0.79 ms	0.93 ms	1.66 ms
LOS C	0.86 ms	1.10 ms	2.54 ms

Finally, Figure 35 shows the PDR for the two levels of service with different traffic mixes. 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 the levels of service B and C, Figure 35 also includes the results obtained for traffic mixes in order to analyse the effects of increasing the number of CVs and CAVs in the use case. 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 use case, the traffic results reported above show that the V2X communications do not negatively impact the traffic KPIs. This is the case because at short distances vehicles can receive packets from sender vehicles with high probability. In particular, the results obtained show that, in the worst-case scenario of traffic mix 3, a PDR higher than 0.8 can be achieved at distances up to 100 m. However, for both traffic mix 1 and 2, a PDR higher than 0.9 can be achieved at distances up to 200 m for both LOS B and C.



(a)



(b)

Figure 35: Packet Delivery Ratio for Use Case 1.3

The overall analysis of the communications KPIs shows that the reliability of the V2X communications is in principle sufficient to satisfy the communication needs of the traffic management measures of Use Case 1.3.

4.1.3 Discussion

In this section we summarise the simulation results after implementing realistic V2X communications (using ns-3) for Use Case 1.3.

In first instance we noted that the simulations with realistic communication did not have any impact on traffic KPIs. The simulation results obtained after implementing the use case and traffic management measures within the iTETRIS framework have confirmed the essential results of Deliverable 4.2 [2], i.e., the proposed traffic management algorithm leads to more efficient and safe traffic flows. We therefore limited our analyses to just the performance of the communications.

All simulations took very long calculation times, especially for the higher LOSs. In addition, with the increased communications overhead, software crashes occurred frequently, requiring us to closely monitor the results for several months and, as a partial solution, to each time restart the crashed simulations. Because of the intractability of some of these simulation runs, and the limited relevance of communication on traffic performance, the number of simulations was limited to a handful of seeds for LOS B and C (every vehicle mix was evaluated each time), and none for LOS D.

Regarding the communications performance, we first analysed the Channel Busy Ratio (CBR) metric, and concluded that it is around or below 35 % in all cases. This is adequate for the deployment of the traffic management measures implemented for this use case. The observed low percentage of CBR will also improve the successful reception of packets and reduce the latency. The latter was observed to be around or below 2.5 ms. This in turn guarantees that the vehicles will receive the traffic management measures with enough time to safely execute the required manoeuvres.

We then analysed the Packet Delivery Ratio (PDR), and concluded that increasing the number of vehicles with V2X capabilities resulted in a decrease of the PDR at the same distance due to the increased interferences and probability of packet collisions.

The overall analysis of the communications KPIs shows that the reliability of the V2X communications is in principle sufficient to satisfy the communication needs of the traffic management measures simulated in Use Case 1.3 and that the V2X communications do not negatively impact the traffic KPIs.

4.2 Use Case 2.1: Prevent ToC/MRM by providing speed, headway, and/or lane advice

4.2.1 Introduction

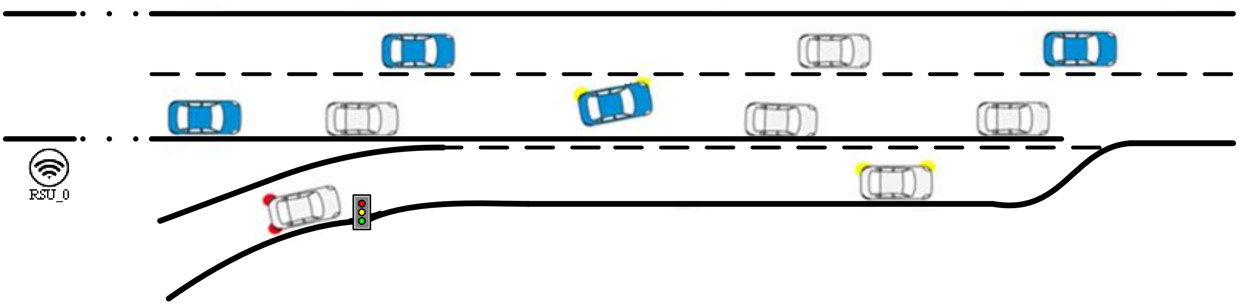


Figure 36: Schematic representation of Use Case 2.1.

To encapsulate the motorway merging Use Case 2.1, it consists of one-lane on-ramp merging into two-lane motorway. Figure 36 shows the schematic representation of Use Case 2.1 in TransAID WP6’s second iteration. Comparing to the schematic layout of the first iteration, an intelligent ramp metering system (controlled by a cooperative merging algorithm) is added to the beginning of the on-ramp. The road-side unit (RSU_0) is placed at the same location (-800 m) as in the first iteration.

The motorway merging use case involves mandatory lane change manoeuvres in a high-speed environment and are therefore complicated in general. The complexity is intensified due to non-field-of-view because of the curvature of the on-ramp, greens/shades, and weather conditions. These impacts cause different levels of view obstruction to different types of vehicles.

As indicated in the first iteration (see [2] Figure 9), different types of vehicles have different cooperative sensing ranges for merging gap selection. In the second iteration, an additional infrastructure component, the intelligent ramp metering system, is added, as shown in Figure 36. The ramp meter releases one vehicle during a green phase (1.5 second) when future merging opportunities exist according to the merging assistant’s calculations. In this way, an AV that used to only observe its adjacent surroundings (see Figure 37 red triangle) for merging opportunities, was released at a “good timing” moment when it can more or less “identify” the intended gap with its driving behaviour and acceleration pattern. The same concept applies to LVs. Comparing to the sensing capability of an AV, a human driver of an LV could observe less limited area on the on-ramp if there is no view obstruction (see Figure 37 blue triangle). With infrastructure assistance, the LV can also benefit from the releasing moment of the ramp meter.

The main objective of Use Case 2.1 is to prevent ToC/MRM of C(A)Vs by providing speed advice and lane advice so that the CAVs on the on-ramp can “see-through” it even before reaching the ramp meter, and that CAVs are equipped with speed/lane advice for a safe and efficient merging before the end of acceleration lane.

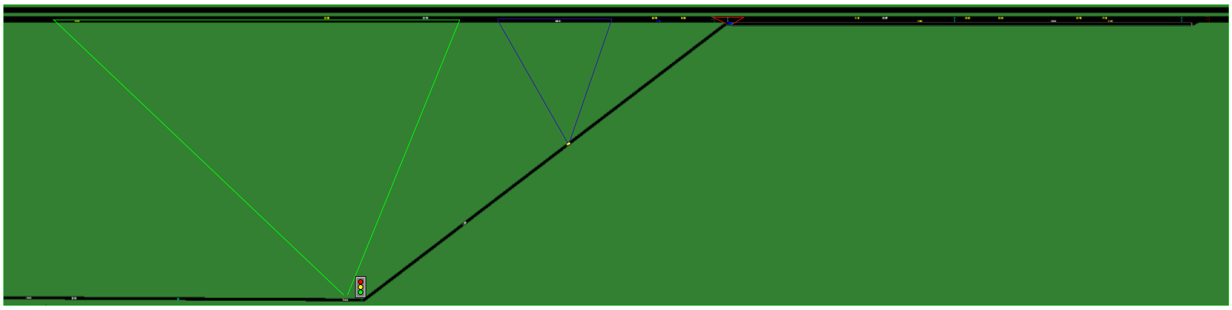


Figure 37: Cooperative sensing range for gap selection for AVs (red triangle), LVs (blue triangle), and CAVs (green triangle), under infrastructure-assisted measures.

Without considering the communication between vehicles and road side infrastructure, the abovementioned objectives are realised through infrastructure-assisted traffic management measures proposed in WP4. Baseline (without traffic management) and infrastructure-assisted traffic management simulations are performed and evaluations were made (see [2]). The results of the traffic management simulations show a significant decrease on the ToC/MRM percentage and vehicle stops at the end of the on-ramp to the acceleration lane.

To obtain a more realistic simulation and performance evaluation, the integration of V2X communication is crucial for Use Case 2.1. In this iteration, the proposed infrastructure-assisted traffic management measures (see WP6 first iteration, TM measures a through f) are simulated including the realistic communication challenges, e.g., information delay, error, or loss, to study the potential impact of realistic communication and robustness of the cooperative merging model in Use Case 2.1.

The use case is shown in Figure 38. A foremost impact of the realistic V2X communications is the limited range of wireless communication of an RSU. This is especially important for Use Case 2.1 with speed advice for high-speed merging manoeuvres where the quality of communication depends on the position of the RSU.

Assuming that typical RSU range has the best performance approximately within 500 m, the placement of a single RSU should meet the requirement of within 500 m upstream of the speed advice end-zone. Since the MRM zone is preserved for 285 m before the end acceleration lane, and the main road entry detectors is much more upstream (-1580 m) for the merging assistant and the ramp meter to predict in time, the RSU is at its optimal position at -800 m as the first iteration. Hence, the intelligent ramp meter will be able to give a green light at a possible gap moment and the speed advice are sent with accuracy and low latency to the CAVs on the on-ramp.

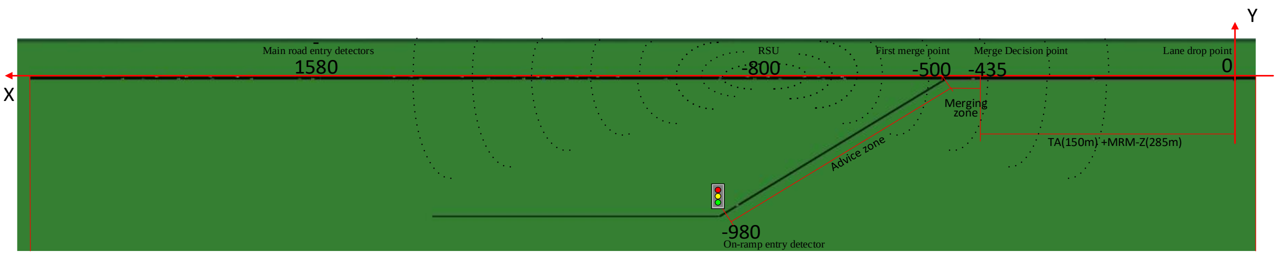


Figure 38: Motorway merging use case.

Since the RSU is still at -800 m as in the first iteration, the message flow still applies. Figure 39 shows the message flow employed in the implementation of Service 2.1 in the first iteration of the project. The only additional component is an intelligent ramp meter, which communicates via wired connection with the RSU and therefore does not generate more messages transmission comparing to the first iteration.

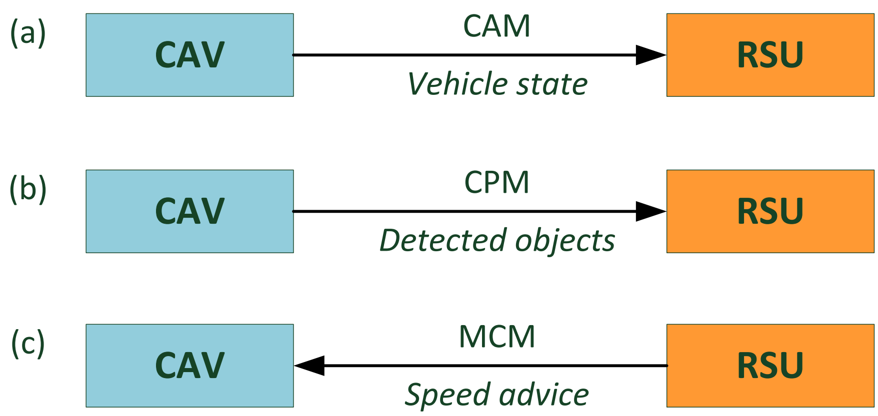
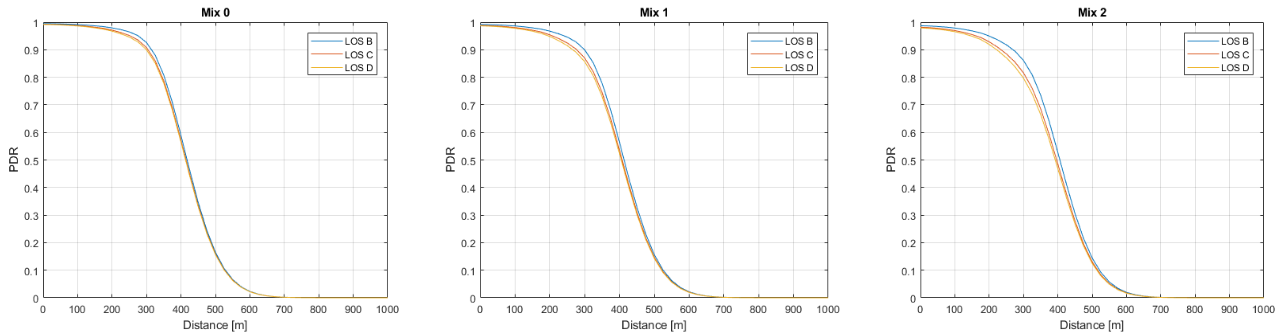


Figure 39: Communications in Use Case 2.1.

Continuing from the first iteration, simulation of TransAID-measured Use Case 2.1 with communication was not performed within iTETRIS because the TM algorithm is designed for field trial portability. The feasibility to port to iTETRIS with enhanced TM measures (intelligent ramp meter adopting the principle of merging assistant in the first iteration) becomes even more cumbersome. Therefore, the same methodology of the first iteration was used here.

The sensitivity of communication errors is provided by the analytical model by UMH. They has developed in [17] an analytical model of the communication performance of IEEE 802.11p. The analytical model provides expressions for the average PDR (Packet Delivery Ratio) as a function of the distance between transmitter and receiver. The models have been validated for a wide range of transmission parameters, such as the transmission power and the data rate, and traffic densities (see Section 2.2.2, Table 1). In Figure 40, the PDR curves used in the first iteration were adapted for the three demand levels (LOS B, LOS C, and LOS D) and for the three vehicle mixes (mix 1, mix 2, and mix 3) in the second iteration. Consolidating into one graph, these nine PER curves have a resolution of 25 m. Interpolation is used between the two closest values in case the distances are not exactly spaced apart by a multiple of 25 m in the simulation.



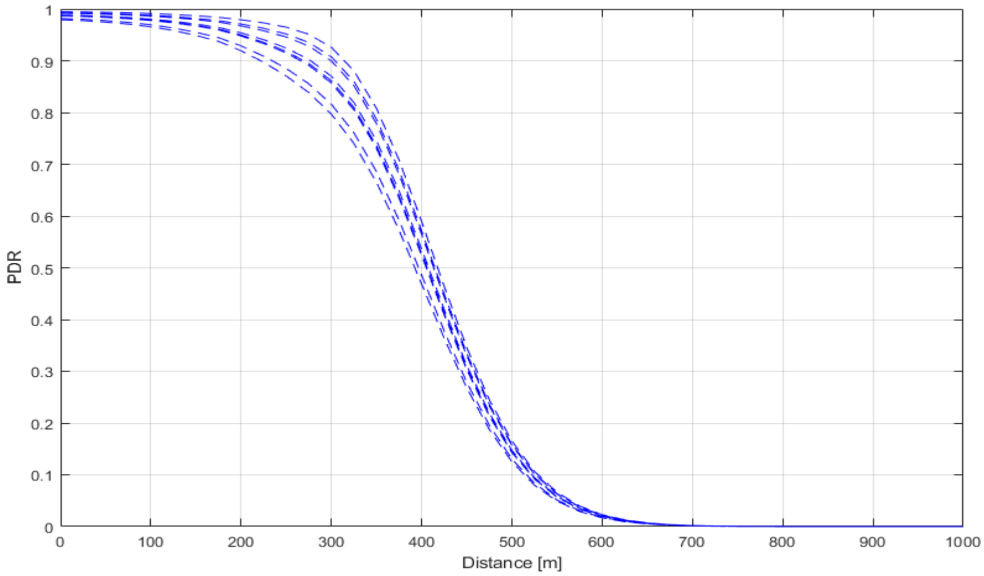


Figure 40: Packet Delivery Ratio (PDR) for different traffic mixes and different traffic demands as a function of communication distance.

Use Case 2.1 implements the full traffic management measures (TransAID measures) of WP4's second iteration: speed advice and lane advice generated by the merging assistant, intelligent ramp metering based on the merging assistant algorithm. The analytical communication model and its functions are integrated as input in the communication simulation module (i.e. a Java application) of Use Case 2.1 that run the simulations with realistic performance of V2X communication using Java and SUMO (version v1_6_0+0873-8d239b3900).

4.2.2 Results

In this section, we present the simulation results obtained for Use Case 2.1 for all combinations of use case parameters (each combination with 10 simulation runs as it was in the first iteration), i.e. levels of service (LOS B, C, and D) and traffic mixes (1, 2, and 3). The measurement of effectiveness is the average ToC percentage of Use Case 2.1 with TransAID measures before and after communication is considered. To prove the efficacy and robustness of the intelligent ramp-metering, the speed-advised motorway merging use case with and without communication was taken into account, and the average ToC percentages were simulated and extracted for all three traffic mixes and three traffic demands of the second iteration. The obtained results were preliminarily analysed using the *t*-test in this section.

Figure 41 presents the average ToC rate of Use Case 2.1 under two categories: without communication (see blue bars) and with realistic communication (see red bars). Note that the Y-axis is a percentage and the results here show significantly low average ToC rates for enhanced TM-measured motorway merging use case under all nine traffic mixes and traffic demands combinations, which is validated by the WP4 simulation results (see [2]).

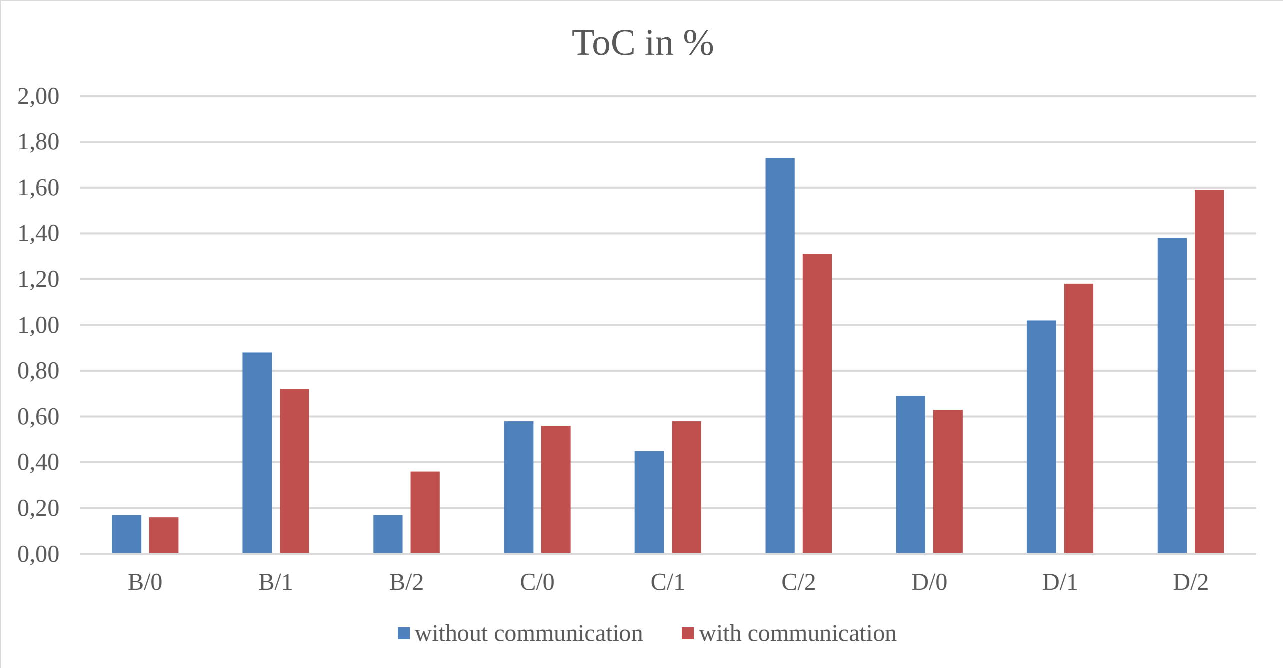


Figure 41: The ToC percentage for TM-measured Use Case 2.1 with (red bars) and without (blue bars) communication.

In statistical methods, Student's *t*-test is a widely-used parametric test to compare the significant differences of a groups' specific variable. In this case, whether or not there is a significant difference in the average ToC rate after adding the realistic communication model.

Assuming that all of the inference conditions have been considered and met, such as random conditions, the normal conditions, and the independent conditions, we start by setting the significance level $\alpha = 0.05$. For the null hypothesis H_0 there is no significant difference between the average ToC rate before and after considering realistic communication and therefore, TransAID-measured Use Case 2.1 / service 2 is unimpaired by adding realistic performance of V2X communication.

Table 20 presents the *t*-test to compare the significant differences of average ToC rates without realistic communication and with realistic communication, under an exemplary combination: LOS D, mix 3. This exemplary combination is considered with the highest vehicular communication load and highest packet error rate which represents the “worst-case scenario”. The *p*-value is 0.27 and greater than the significance level (0.05). Therefore, the null hypothesis H_0 is inferred to be true. For this “worst-case scenario”, the average ToC rate seems irrelevant to the performance of realistic V2X communication. For each scenario combination of different LOSs and different mixes, the same test procedures are performed to compare the results before and after adding vehicular communication in order to examine whether the average ToC is negatively affected.

Table 20: Exemplary *t*-test of average ToC rate with and without realistic communication, under LOS D, mix 3.

Simulation run #	ToC in % (without communication)	ToC in % (with communication)
1	2.06	2.06
2	1.44	2.39
3	0.52	1.03
4	1.64	2.15
5	0.52	1.55
6	2.14	1.60
7	1.40	0.00
8	0.58	0.58
9	1.36	1.81
10	2.15	2.69
p-value	0.27	

Table 21 lists the *p*-values for all scenario combinations. These are all higher than the significance level (0.05), which leads to the same conclusion that the average ToC rates of all traffic management scenarios of Use Case 2.1/Service 2 have no significant difference due to consideration of realistic communication.

Table 21: *p*-values of all nine scenarios' *t*-tests.

t-test scenario	B/0	B/1	B/2	C/0	C/1	C/2	D/0	D/1	D/2
p-value	0.49	0.28	0.22	0.48	0.27	0.10	0.41	0.32	0.27

Finally, Figure 42 shows the average packet failed ratio of TransAID-measured Use Case 2.1 with consideration of realistic communication for the three different levels of service and three different traffic mixes. The aforementioned analytical model developed by UMH shows the PDR (Packet Delivery Ratio, see Figure 40) in realistic V2X communication and indicates the probability of successfully receiving a packet at a given communication distance. TransAID-measured Use Case 2.1 integrated this model and ran simulations with realistic V2X messages transmission, with increasing volumes of CVs and CAVs (traffic mixes 1, 2, and 3) and increasing traffic demands (LOS B, C, and D).

The simulation results from Figure 42 indicate that the packet failed ratios range between 2 % and 8 %. The trend of average packet failed ratios in this figure validates the communication model used in Use Case 2.1 and the analytical model as inputs. As expected, Figure 42 shows the packet failed ratio increases with an increased number of V2X-capable vehicles due to increased interferences and a higher probability of packet loss.

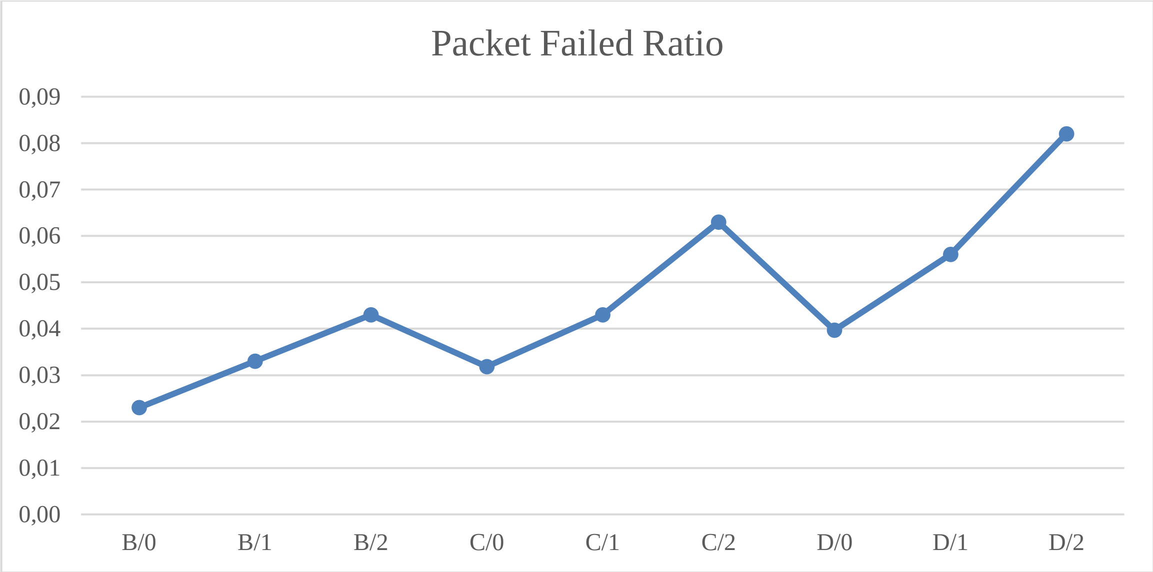


Figure 42: Average packet failed ratio of TransAID-measured Use Case 2.1 with realistic communication under nine combinations of different LOSs and different mixes.

4.2.3 Discussion

In this section, we summarise the simulation results obtained after implementing realistic V2X communication in TransAID-measured Use Case 2.1. Despite that the V2X communication was not simulated within iTETRIS framework, the UMH analytical model and the embedded communication module of traffic management Use Case 2.1 have been validated by the packet fail ratio simulation results of nine combinations (three LOSs and three mixes), as shown in Figure 42.

In addition, the simulation results of average ToC rates under each combination were low and ranging between 0.2 % and 2 % (see Figure 41, blue bars). This was also confirmed by Deliverable 4.2 [2]. The average ToC rates of each scenario combination effectively decreased with enhanced traffic management measures that provide speed advice, lane advice, and intelligent ramp metering based on the merging assistant algorithm.

In the previous section, the main simulation results of average ToC rates with and without communication were compared, as shown in Figure 41. A *t*-test of each scenario combination examined the significant differences of average ToC rates. All *t*-tests are inferred to be true and therefore, the realistic communication setup is confirmed to have not impaired the execution of TransAID-measured Use Case 2.1/Service 2, despite higher penetration rates of C(A)Vs (LOS B, C, and D) that generate a higher communication load. The robustness of the communication protocols ensured that the main KPI of average ToC rates is not negatively affected by the vehicular communication. The implementing of the RSU location proves to have optimal coverage in the area, and the average ToC rates are greatly reduced in the second iteration with enhanced traffic management using intelligent ramp metering, both for the cases with and without realistic communications.

Finally, we pay attention to the lessons learned for several aspects of Use Case 2.1, which should be kept in mind for future simulation work:

a) In retrospect, the merging assistant in Use Case 2.1 was programmed in Java for the portability of a real-world prototype. These traffic management measures (speed/lane advice) and enhanced traffic management measure (intelligent ramp metering) of the second iteration were based on the merging assistant that has a different structure as iTETRIS C++

written applications. Therefore, we were not able to carry out the realistic V2X communication inside the iTETRIS framework for Use Case 2.1. The trade-off between field prototype deployment and communication simulation should be considered carefully case by case.

b) In WP6's second iteration, Use Case 2.1 simulations have chosen the same RSU position as in the first iteration because of the optimal communication radius and its coverage. At the time this document was written, the WP7 field test of Use Case 2.1 has been performed on the A13 highway in the Netherlands. The advice of the RSU location (learned from WP6 first iteration simulation) has been adopted in the field work. But we have noticed the following trade-off:
    a. The communication range of the RSU location and the seclusion of the prototype RSU equipment (aiming for no driver behaviour change) can cause discrepancies in the RSU location between the WP6 simulation and the WP7 field test.
    b. Since the merge area is chosen and kept deliberately long enough for the timely reception of speed advice, and CVs/CAVs' reaction and execution of the speed following, a redundant RSU and the effect of its communication could be considered in the future study.
    c. Following the above point, the realistic communication simulation of a short on-ramp/acceleration lane highway merging layout could be interesting for a future study.

c) Results from Section 4.2.2 have shown that adding realistic communications to the traffic management measured Use Case 2.1 did not cause negative impact to the robustness of preventing ToC of TransAID measures. The RSU software and its central TM logic reside in the RSUs itself. This is also the case in the WP7 field test.

d) Comparing to the first iteration, WP6's second iteration has added the enhanced traffic management measure of ramp metering based on the merging assistant algorithm. The results from Section 4.2.2 have shown that the average ToC rate is significant lower, compared to the first iteration. No extra communication upon adding ramp metering is needed, as it should be directly connected/wired with the ramp metering software (based on the RSU software).

e) Based on the observation of WP6's second iteration simulation, the intelligent ramp metering has regulated and prepared the CVs/CAVs before entering the on-ramp: if the ramp metering calculated and found possible future merging gap, it released the CAV without letting it lose its speed advantage. If the ramp metering did not found an imminent future merging gap, it stopped the CAVs until otherwise. As soon as a CAV is released by the ramp metering to accelerate from 0 km/h on the on-ramp, the speed advice is transmitted with an MRM message that prepared the vehicle to smoothly merge in the merge area. The simulation results here showed this advantage, especially when the acceleration lane is not at the desirable length in some cases.

4.3 Use Case 2.3: Intersection handling due to incident

4.3.1 Introduction

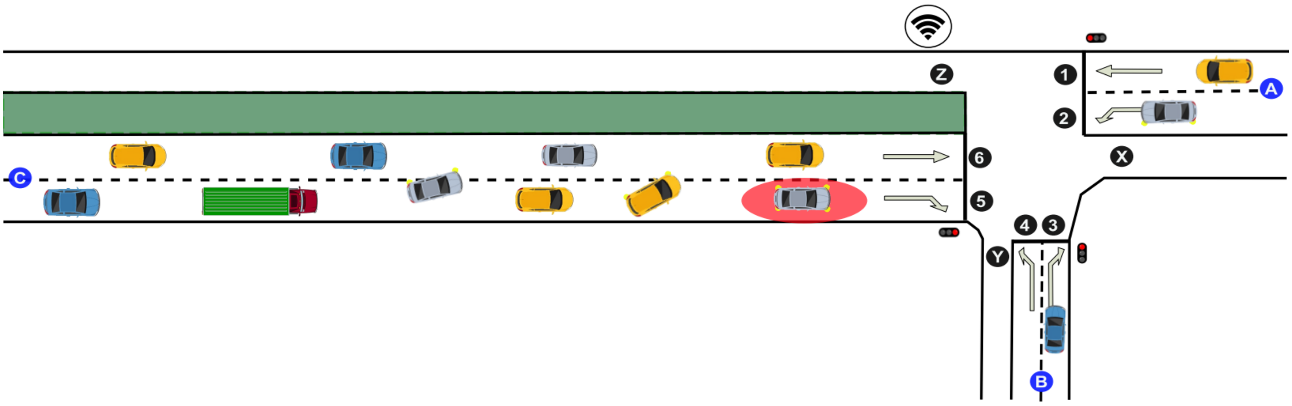


Figure 43: Layout of Use Case 2.3.

Figure 43 gives a high-level schematic overview of the use case. An incident occurs just before the stop line of the right turning traffic lane on the west approach (approach C, lane 5). The incident is blocking lane 5 approximately 35 m before the stop line and therefore vehicles driving on this lane will need to use the through traffic lane (approach C, lane 6) to drive around the incident. In the baseline scenario (see [18], paragraph 4.2.3), the RSU of the TLC will be informed about the incident on lane 5, and share its relevant information with the approaching CAVs/CVs. The warning information and location is shared via DENM. Depending on whether the (C)AV can recognise the situation, either a ToR is issued which ends up in a ToC or an MRM, or the (C)AV recognises the situation. In both cases, automated and manually driven vehicles will try to merge into lane 6 to overcome the incident. A portion of the vehicles in automated mode which do not know how to turn right safely are assumed to continue their journey towards lane *x* and find a new route. Manually driven vehicles and another portion of the vehicles driving in automated mode are assumed to turn right at the junction.

Without considering the communication between vehicles and road-side infrastructure, the abovementioned objectives are realised through the infrastructure-assisted traffic management measures proposed in WP4. Baseline (without traffic management) and infrastructure-assisted traffic management simulations are performed and evaluations were made (see [2]).

To obtain a more realistic simulation and performance evaluation, the integration of V2X communication is done for Use Case 2.3. In this iteration, the proposed infrastructure-assisted traffic management measures (see Figure 44 and Table 22) are simulated including the realistic communication challenges, e.g., information delay, error, or loss, to study the potential impact of realistic communication and robustness. Given the information that is relayed to the approaching vehicles, CAVs and CVs:

- Will receive information about the incident itself (position, type etc.).
- Will receive a reduced speed advice.
- Are advised to use lane 6 to prepare for the right turn to the south arm of the intersection.

Figure 44 shows the steps taken when an incident occurs in front of the traffic light controller and how a rollback is done in case the incident is resolved.

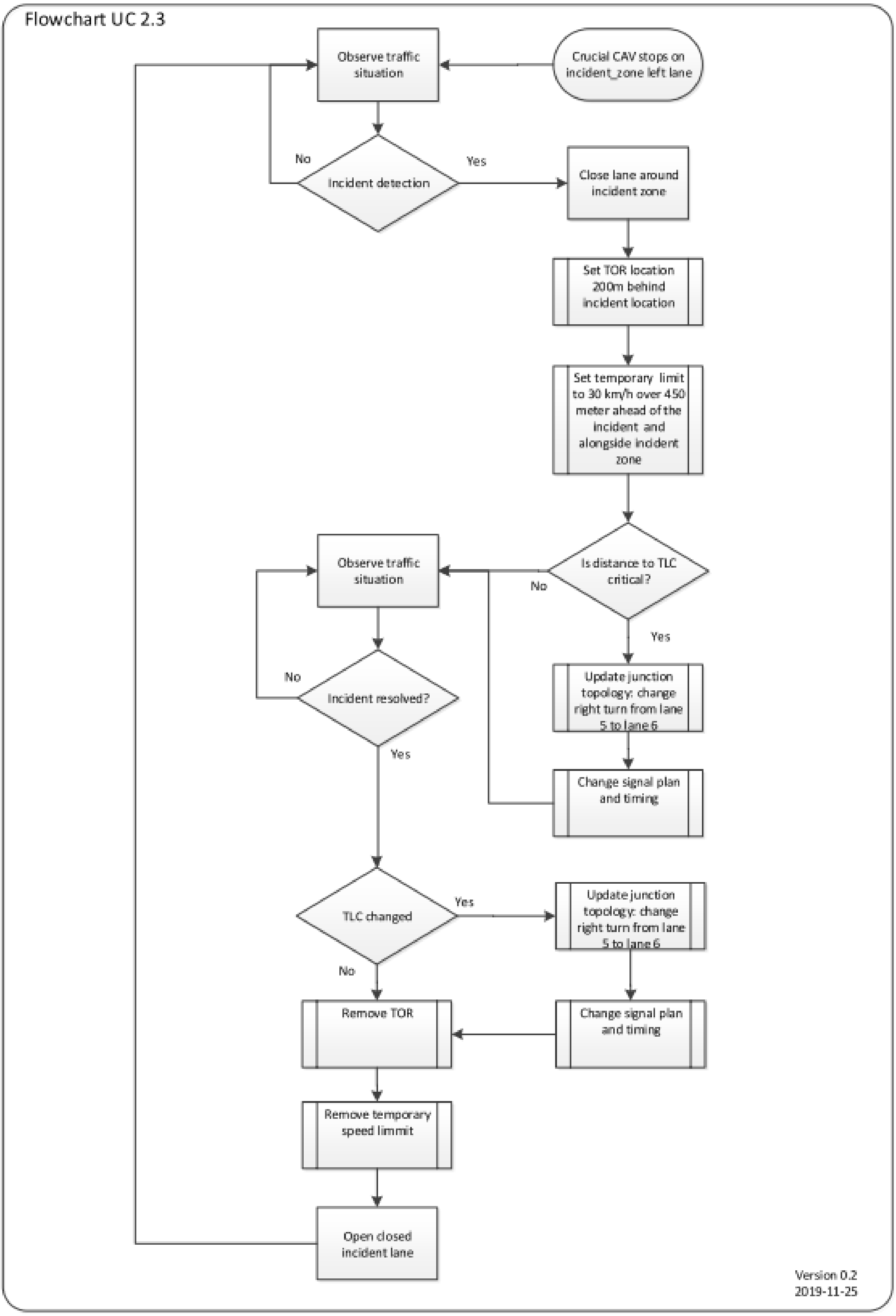


Figure 44: Flow chart of traffic management operations for Use Case 2.3.

On reception of the alert message from the incident, the RSU will start to implement the traffic management measures as described in Table 22. Due to the specific use case implementation, all CAVs are able to make the right turn in a safe way and will not continue straight as in the baseline scenario.

Table 22: Traffic management measures Use Case 2.3.

<table>
<tr><th>Step</th><th>Description</th><th>Action</th></tr>
<tr><td>1</td><td>Set ToR location for CVs</td><td>150 m into the lane change zone</td></tr>
<tr><td>2</td><td>Close lane at incident zone</td><td>close connection to incident lane safe_spot_zone</td></tr>
<tr><td>3</td><td>Set speed limit on the lane change and incident zones</td><td>Set speed limit to 30 km/h on
safe_spot_zone and incident_zone</td></tr>
<tr><td>4</td><td>Change right turn from lane 5 to lane 6</td><td>Update junction topology</td></tr>
<tr><td>5</td><td>Update signal timing
• New timing
• Signal group 10 set to red in last two phases</td><td>
<table>
<tr><th>base</th><th>TM</th><th>5</th><th>6</th><th>7</th><th>9</th><th>10</th><th>11</th></tr>
<tr><td>82</td><td>92</td><td>G</td><td>r</td><td>r</td><td>r</td><td>G</td><td>G</td></tr>
<tr><td>3</td><td>3</td><td>G</td><td>r</td><td>r</td><td>r</td><td>y</td><td>y</td></tr>
<tr><td>16</td><td>11</td><td>G</td><td>G</td><td>G</td><td>r</td><td>r</td><td>r</td></tr>
<tr><td>3</td><td>3</td><td>y</td><td>y</td><td>y</td><td>r</td><td>r</td><td>r</td></tr>
<tr><td>18</td><td>13</td><td>r</td><td>r</td><td>G</td><td>G</td><td>~~G~~ r</td><td>r</td></tr>
<tr><td>3</td><td>3</td><td>r</td><td>r</td><td>y</td><td>y</td><td>~~y~~ r</td><td>r</td></tr>
</table>
</td></tr>
</table>

The timing plan is calculated with COCON[2]. The new green time for signal group 5 is a counter measure for the loss of capacity due to the lane closure of the signal group.

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 the broadcast of messages by the RSU and vehicles. The RSU broadcasts MAPEM and DENM messages, the SPATEM was simulated by SUMO. In case of a CAV that cannot handle the situation and a ToR is issued, an MCM will be broadcast by the vehicle with the ToC information to inform the RSU and other CAVs in the vicinity.

Less regular reception of state updates might occur, e.g., due to transmission errors, and consequently the CAVs might receive imperfect information. This was done in a linear fashion for the traffic management scenario since we expect the algorithm to be rather robust, i.e., the MAPEM and DENM were broadcast every 1000 ms, CAM, MCM, and CPM every 100 ms, so that at the approach of the junction, vehicles will receive multiple updates making the message flow rather robust.

[2] COCON is a Dutch software tool to calculate fixed time signal control plans. It is the most used software suite in the Netherlands. See also https://www.wegenwiki.nl/COCON

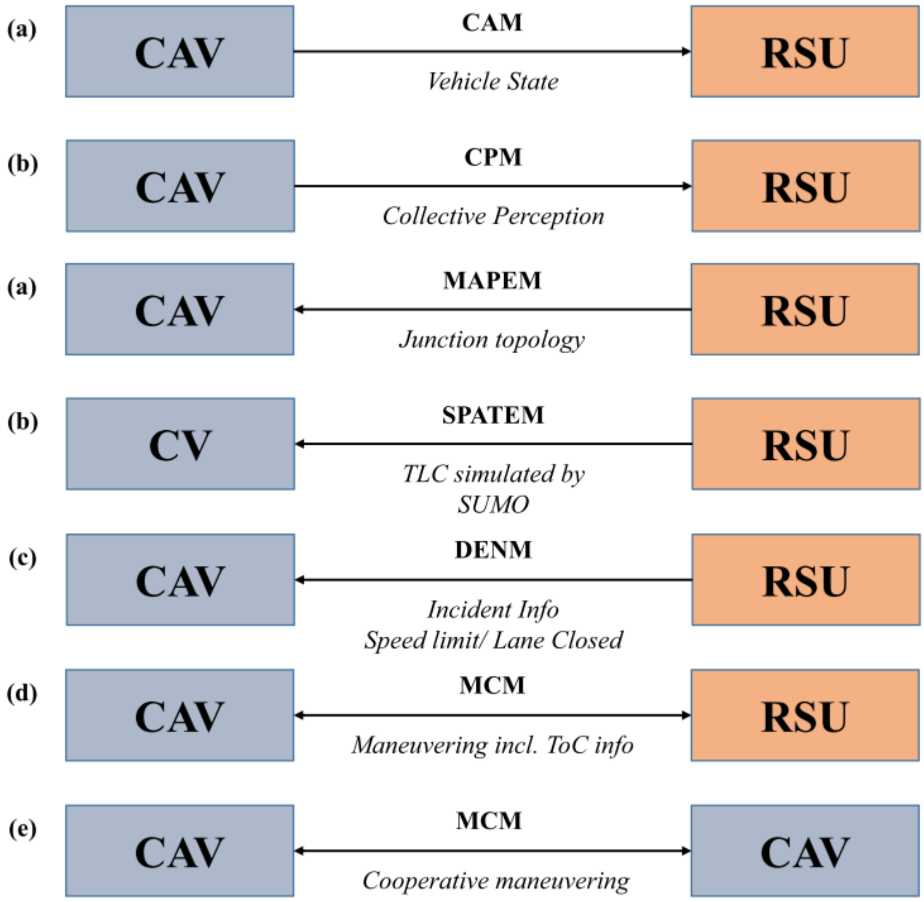


Figure 45: Communication message types exchanged in Use Case 2.3.

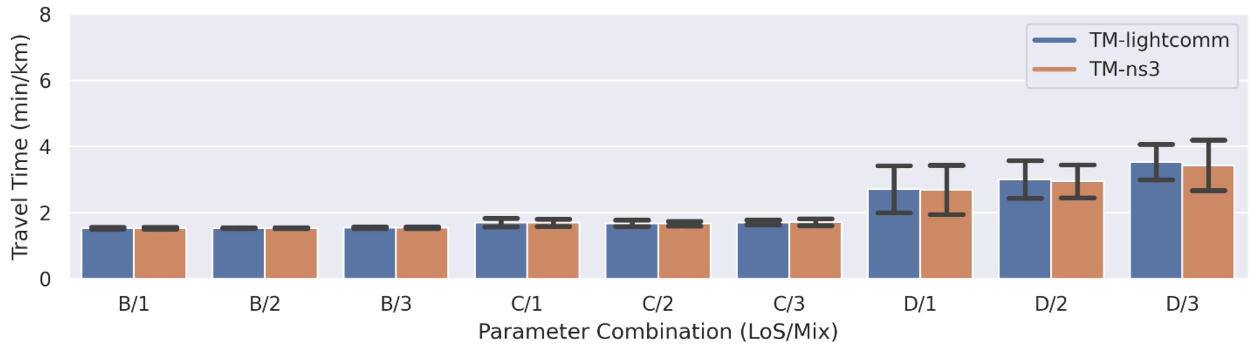
The parts of the communication protocol for Service 2.3 regarding the TM procedures involve four types of message exchange of which three are transmitted by the RSU: a MAPEM containing an update of the junction topology, a SPATEM containing TLC signalling (handled by SUMO), and a DENM containing incident info and lane closure information. The CAVs, receiving the information from the RSU, compute if they can cope with the presented situation. The CAVs that cannot handle the situation will trigger a ToR. The ToC information can be included in the CAM and MRM messages of the vehicle. In the iTETRIS coding this was not included; The ToC status is recognised thru SUMO/TRaCI. For an overview of all the messages and flows, see Figure 45.

4.3.2 Results

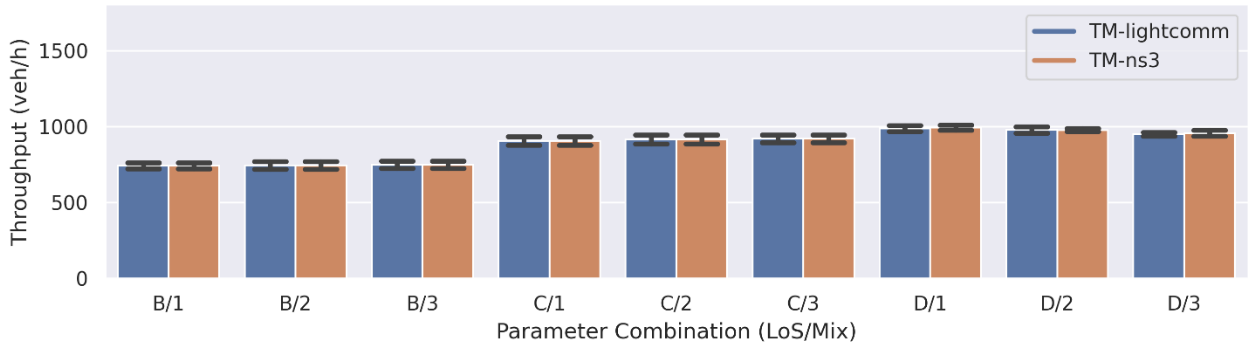
In this section, we describe the simulation results obtained for this use case. The main objective of the performance evaluation is to inspect the robustness of the TM procedures with respect to the simulation of realistic V2X data communication. To this end, we simulated all combinations of use case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

Traffic

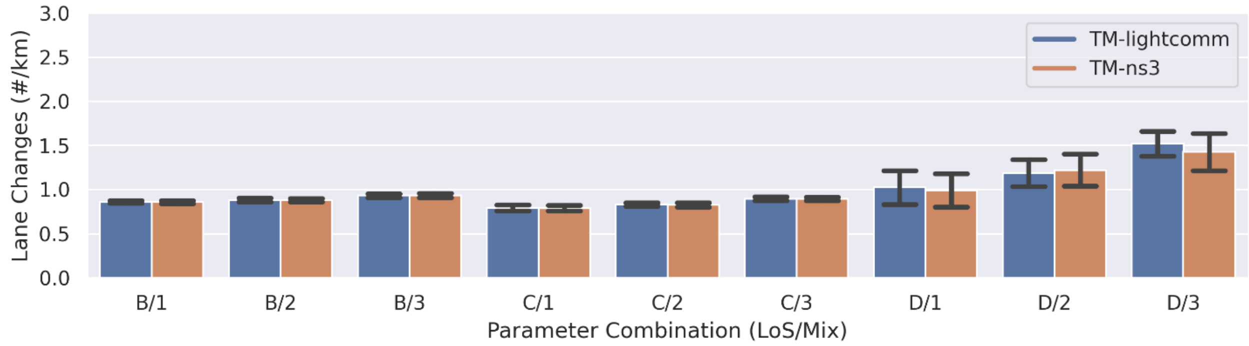
As in Deliverable 4.2 [2], we inspected the performance aspects traffic efficiency, traffic dynamics, traffic safety, and environmental impact, quantified with the network-wide traffic KPIs “travel time”, “throughput” and “lane changes”, “critical events”, and “CO_2 emissions”, respectively (cf. [14]). Additionally, we inspected the number of TORs and MRMs, which are specific to TransAID.


Travel Time (min/km)
0
2
4
6
8
TM-lightcomm
TM-ns3
B/1
B/2
B/3
C/1
C/2
C/3
D/1
D/2
D/3
Parameter Combination (LoS/Mix)

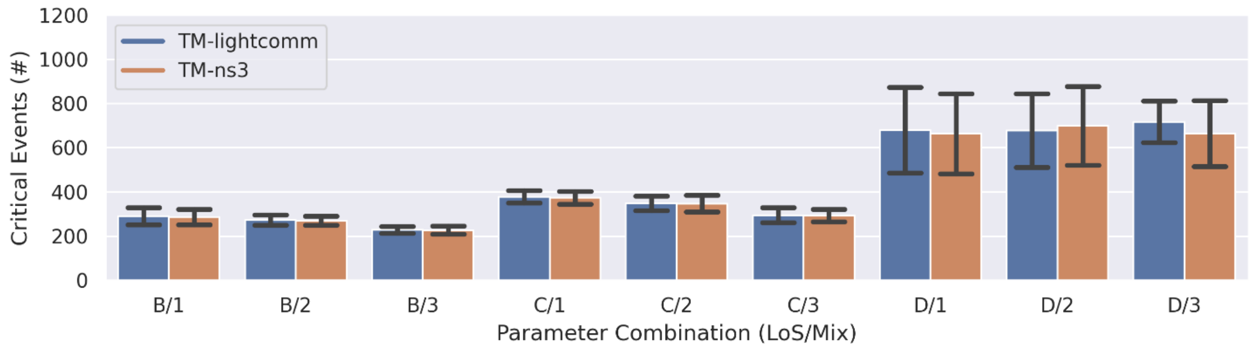
(a)


Throughput (veh/h)
0
500
1000
1500
TM-lightcomm
TM-ns3
B/1
B/2
B/3
C/1
C/2
C/3
D/1
D/2
D/3
Parameter Combination (LoS/Mix)

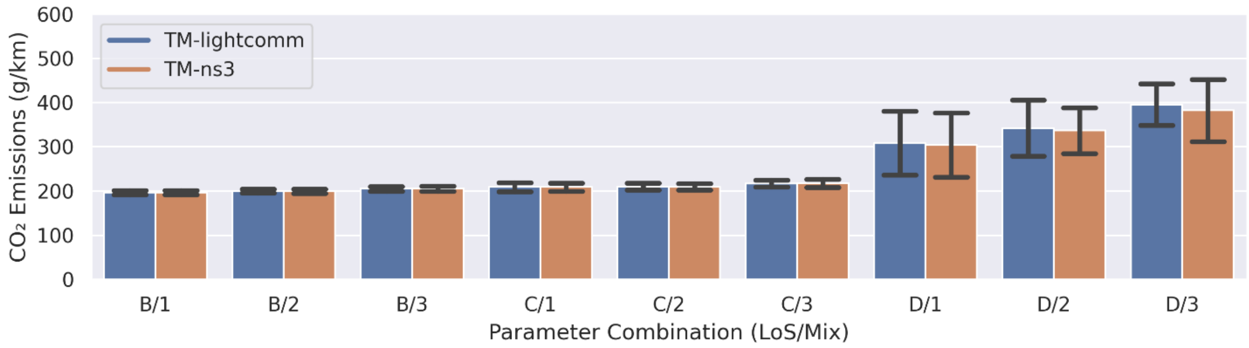
(b)


Lane Changes (#/km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
TM-lightcomm
TM-ns3
B/1
B/2
B/3
C/1
C/2
C/3
D/1
D/2
D/3
Parameter Combination (LoS/Mix)

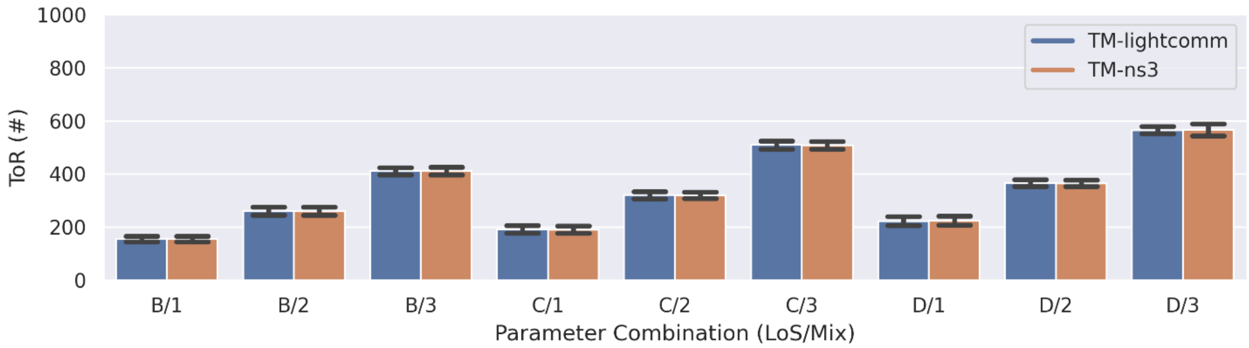
(c)


Critical Events (#)
0
200
400
600
800
1000
1200
TM-lightcomm
TM-ns3
B/1
B/2
B/3
C/1
C/2
C/3
D/1
D/2
D/3
Parameter Combination (LoS/Mix)

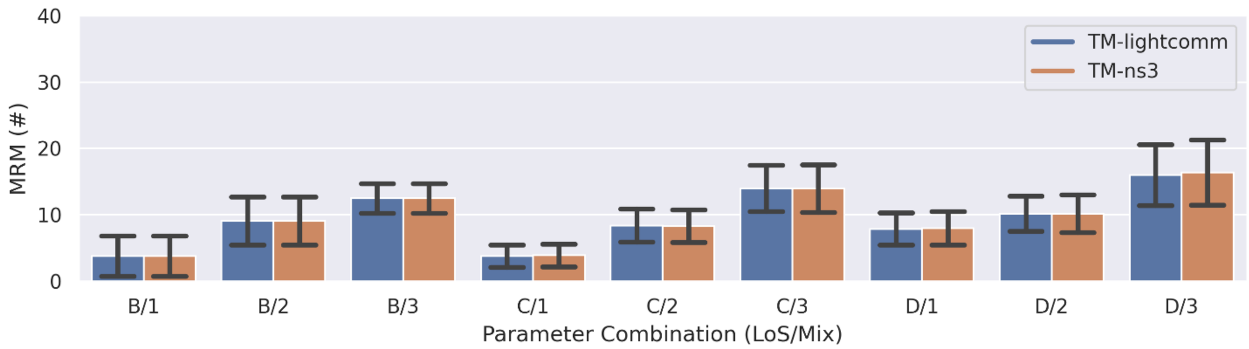
(d)



(e)



(f)

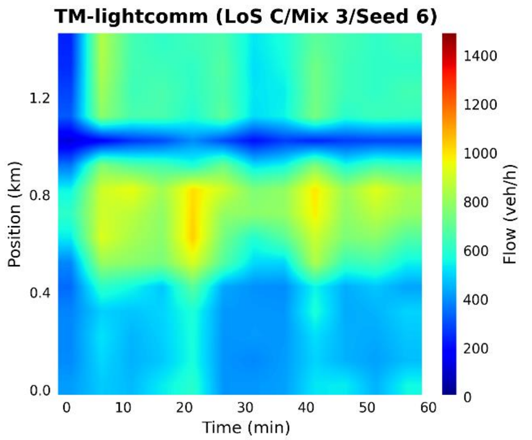


(g)

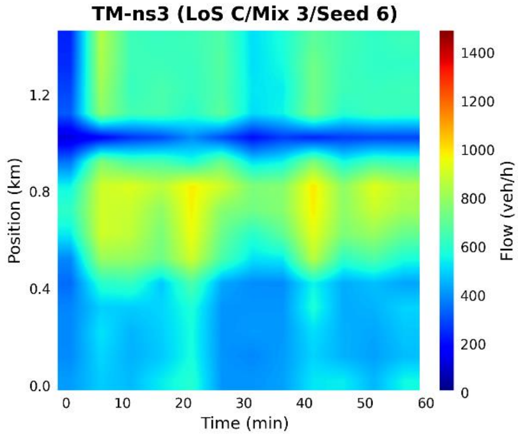
Figure 46: Network-wide simulation results for Use Case 2.3. Error bars show the standard deviation among ten replications over one-hour simulation time for the corresponding parameter combination.

Figure 46 depicts average network statistics. Mean values and standard deviation between ideal (i.e. LightComm) and realistic (i.e. ns-3) communications are, for the most part, similar for each statistic category and parameter combination. Only for LOS D vehicle mix 3, a difference in the standard deviation is observed. For LOS D vehicle mix 2, a similar effect can be seen but the other way around (between LightComm and ns-3). See next paragraph.

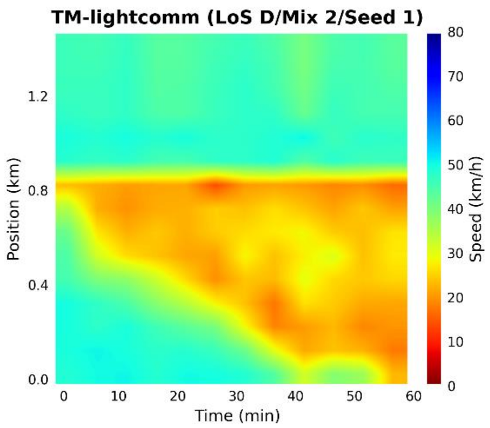
On the whole, the simulation of realistic communication protocols did not adversely impact the efficacy of the simulated traffic management strategy.



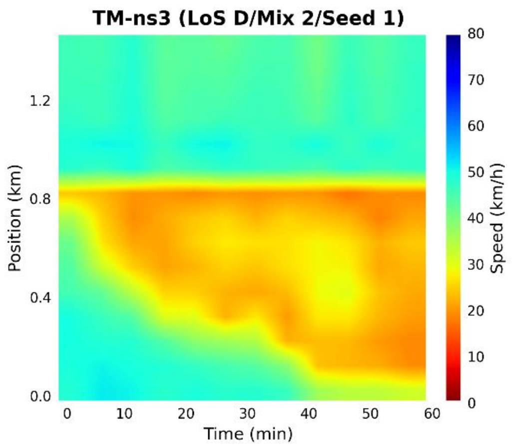
(a)



(b)



(c)



(d)

Figure 47: Example spatio-temporal plots visualising KPIs flow (a, b) and speed (c, d), respectively, for Use Case 2.3. For both KPIs, ideal (a, c) and realistic (b, d) communication results are shown side-to-side for easier comparison.

Similar observations are made when considering local network statistics. The traffic patterns observed in the spatio-temporal plots of speed and flow match between the LightComm and ns-3 cases irrespective of the examined parameter combination and simulation seed (an example is shown in Figure 47) except for LOS D. For LOS D traffic mix 2 and 3, we observe some differences between LightComm and ns-3, mainly for lane changes and critical events.

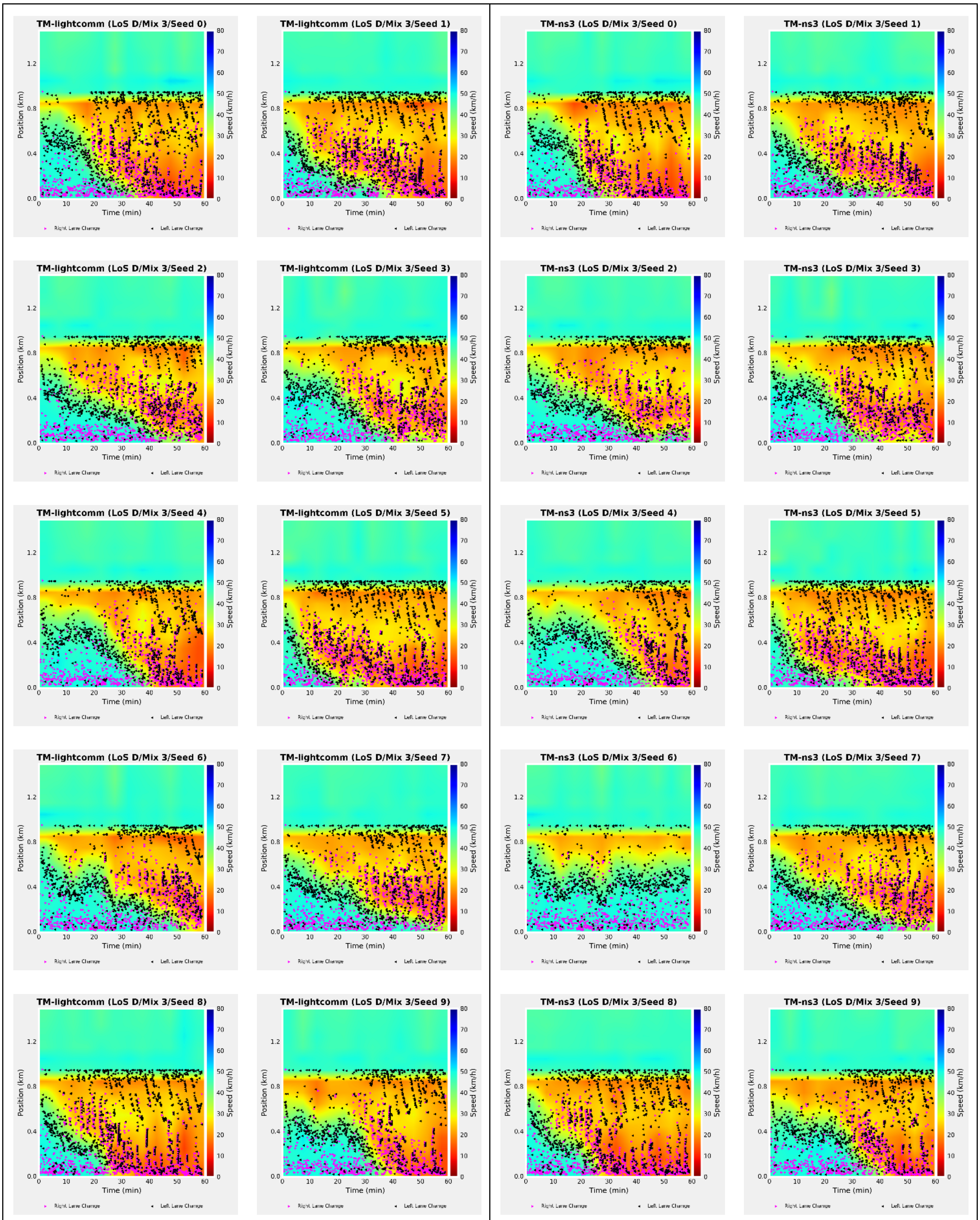
To see what the differences are between the 10 simulated seeds, the speed-lane changes were analysed, being the most profound representation. Mainly seed 7 and 8 differ between LightComm and ns-3 simulation. Figure 48 shows the simulation results of the 10 seeds (note that the numbers range from 0 for seed 1 to 9 for seed 10) for LOS D mix 3. Looking at the overview of the plots, the ns-3 simulations seem to have, in the more comparable plots, a bit of an earlier build-up of lower speeds, e.g., more congestion. Only simulation results of seed 7 are the other way around. To investigate the differences two steps were followed:

1. Impact of communication on the traffic flow and behaviour
2. Investigate the inputs and logs of the SUMO simulation

As a first step, the communication results were analysed in more detail. Less congestion in seed 6 gave better performance indicators for communication. CBR and PDR were for all the seeds within normal expected boundaries. With more traffic in the network in LOS D, the PDR drops somewhat what could explain a denser traffic but the throughput of all the seeds are similar compared with LightComm.

The next step was to investigate the input files, simulation results, and log files. The ns-3 simulation was also run in the SUMO GUI to look for anomalies or differences. The traffic input and throughput of the network were the same between LightComm and ns-3 and no errors were encountered. This deeper investigation did not shed a light on or could explain the observed differences.

Investigations within the available given timeframe did not explain the different behaviour of seed 7, and as such, the seed should be considered an outlier.



(a)	(b)

Figure 48: Combined speed and lane change events LOS D Mix 3 seed 1(0) to 10(9) for Use Case 2.3. For both KPIs, ideal (a) and realistic (b) communication results.

Communication

This section analyses the impact of the traffic management measures in the performance of V2X communications and about the outliers mentioned in the previous section. First, we analyse the congestion level of the V2X communications channel through the Channel Busy Ratio (CBR) metric. The CBR is defined as the percentage of time that the channel is sensed as busy. Table 23 shows the average CBR for all vehicles in the simulation. The results are reported for all combinations of use case parameters, i.e. levels of service (LOS B, C and D) and traffic mixes (1, 2, 3). The obtained results show that for all the combinations of use case parameters, the CBR is around or below 26 % (for the scenario with LOS D 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 26 % of the time. Thus, the traffic management measures implemented for the TransAID Use Case 2.3 are not creating an excessive V2X communication load and vehicles can access the channel to transmit their messages without any negative impact on the communications.

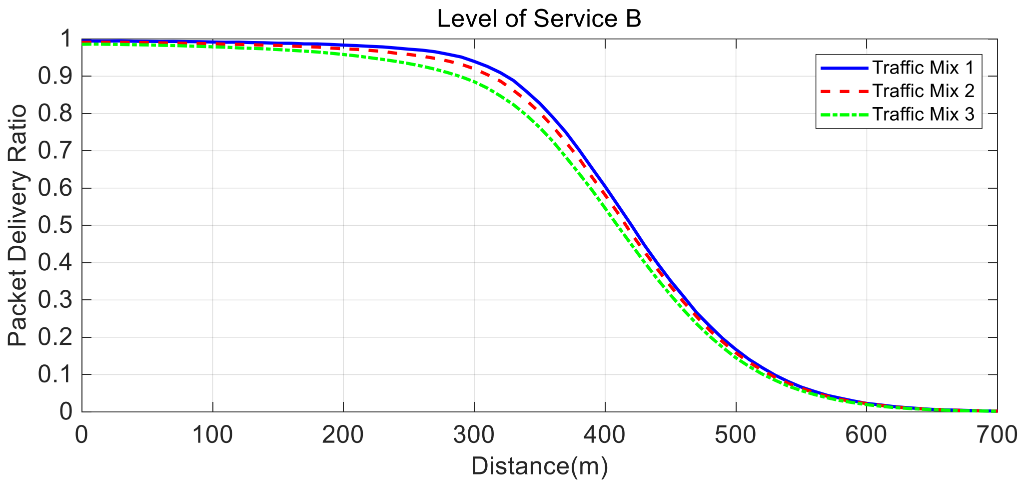
Table 23: Channel Busy Ratios for Use Case 2.3

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	3.63 %	5.57 %	8.42 %
LOS C	4.76 %	7.21 %	11.26 %
LOS D	9.62 %	16.97 %	26.52 %

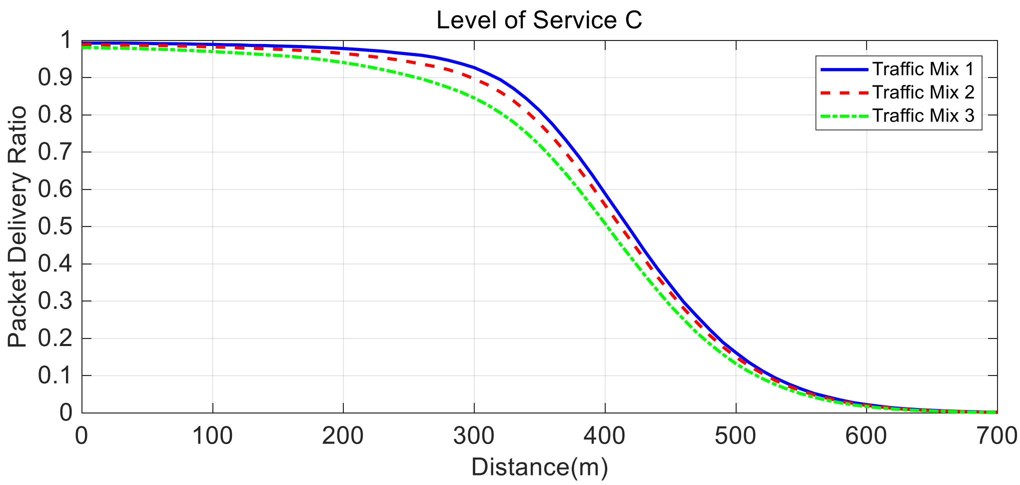
Table 24: Latencies for Use Case 2.3.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	0.60 ms	0.63 ms	0.68 ms
LOS C	0.61 ms	0.65 ms	0.74 ms
LOS D	0.71 ms	0.96 ms	1.77 ms

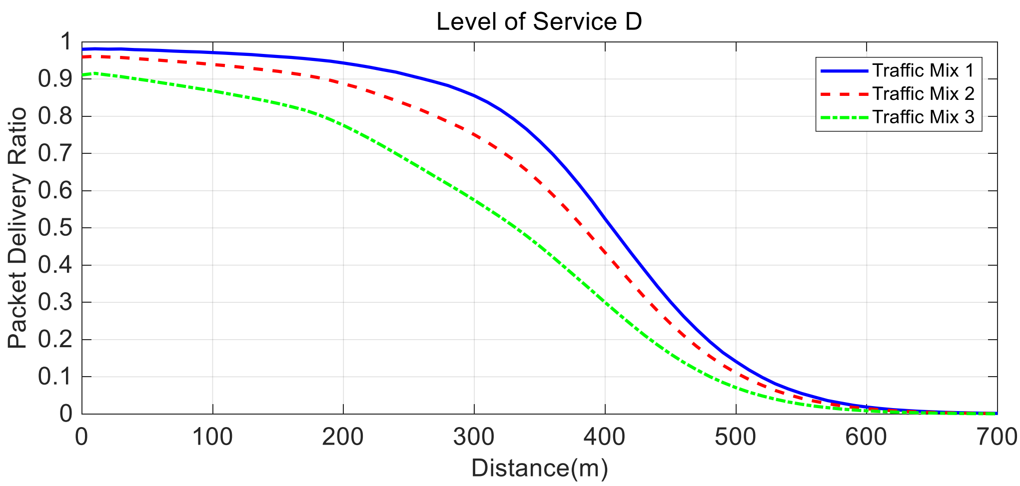
The observed low percentage of CBR will improve the successful reception of packets and reduce the latency. Table 24 shows the average latency of the V2X communication messages transmitted during the Use Case 2.3 simulations. The latency measures the time elapsed between the transmission and reception of a packet at the application/facility layer. We can observe that the average latency measured for all the combinations of use case parameters is around or below 1.7 ms. These latency values guarantee that the vehicles will receive the traffic management measures with enough time to safely execute the required manoeuvres.



(a)



(b)



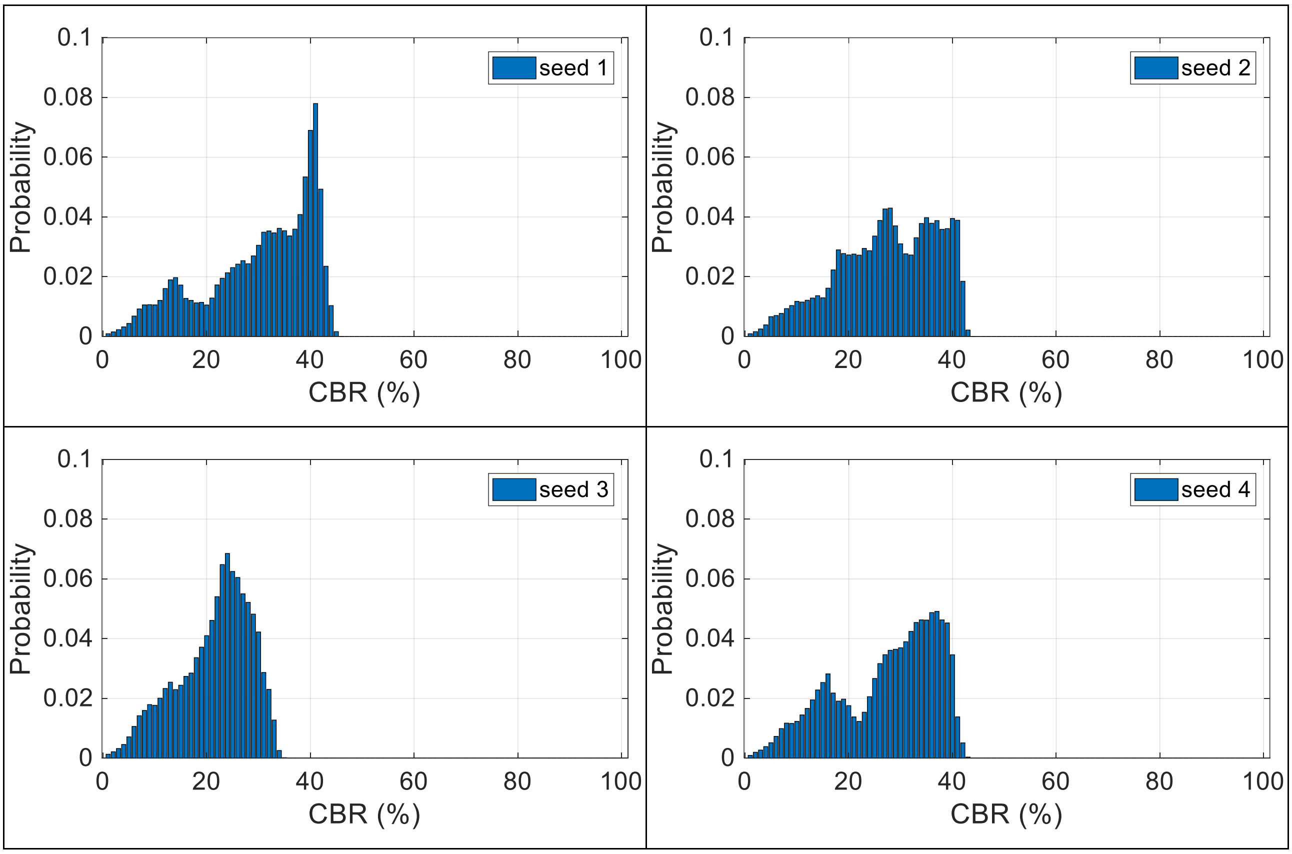
(c)

Figure 49: Packet Delivery Ratio for Use Case 2.3.

Finally, Figure 49 shows the PDR for the three different levels of service with different traffic mixes. The Packet Delivery Ratio (PDR) defined as the probability of successfully receiving a message as a function of the distance between the transmitting and receiving vehicles. The reported PDR represents the average of all V2X transmissions occurring during the simulations. For each one of the levels of service, Figure 49 also includes the results obtained for traffic mixes in order to analyse the effects of increasing the number of CVs and CAVs in the use case. As expected, increasing the number of vehicles with V2X capabilities results in a slight decrease of the PDR at the same distance due to the increased interferences and probability of packet collisions. 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. Despite this PDR decrease with the increasing connected vehicles share in the use case, the traffic results reported above show that the V2X communications do not negatively impact the traffic KPIs.

The overall analysis of the communications KPIs shows that the execution of the traffic management measures for TransAID Use Case 2.3 under realistic conditions does not negatively impact to the performance of the V2X communications.

To address the outlier issue discussed in the previous traffic subsection, we additionally computed the CBR and PDR for individual seeds from 1 to 10 for the scenario LOS D Mix 3 configuration. Figure 50 shows that the reported CBR for seed 7 is significantly less when compared with other seeds which improved the PDR for seed 7 (see Figure 51). This different behaviour of seed 7 once again aligns with the results shown in the previous subsection and hence justifies the above claim that seed 7 can be considered as an outlier.



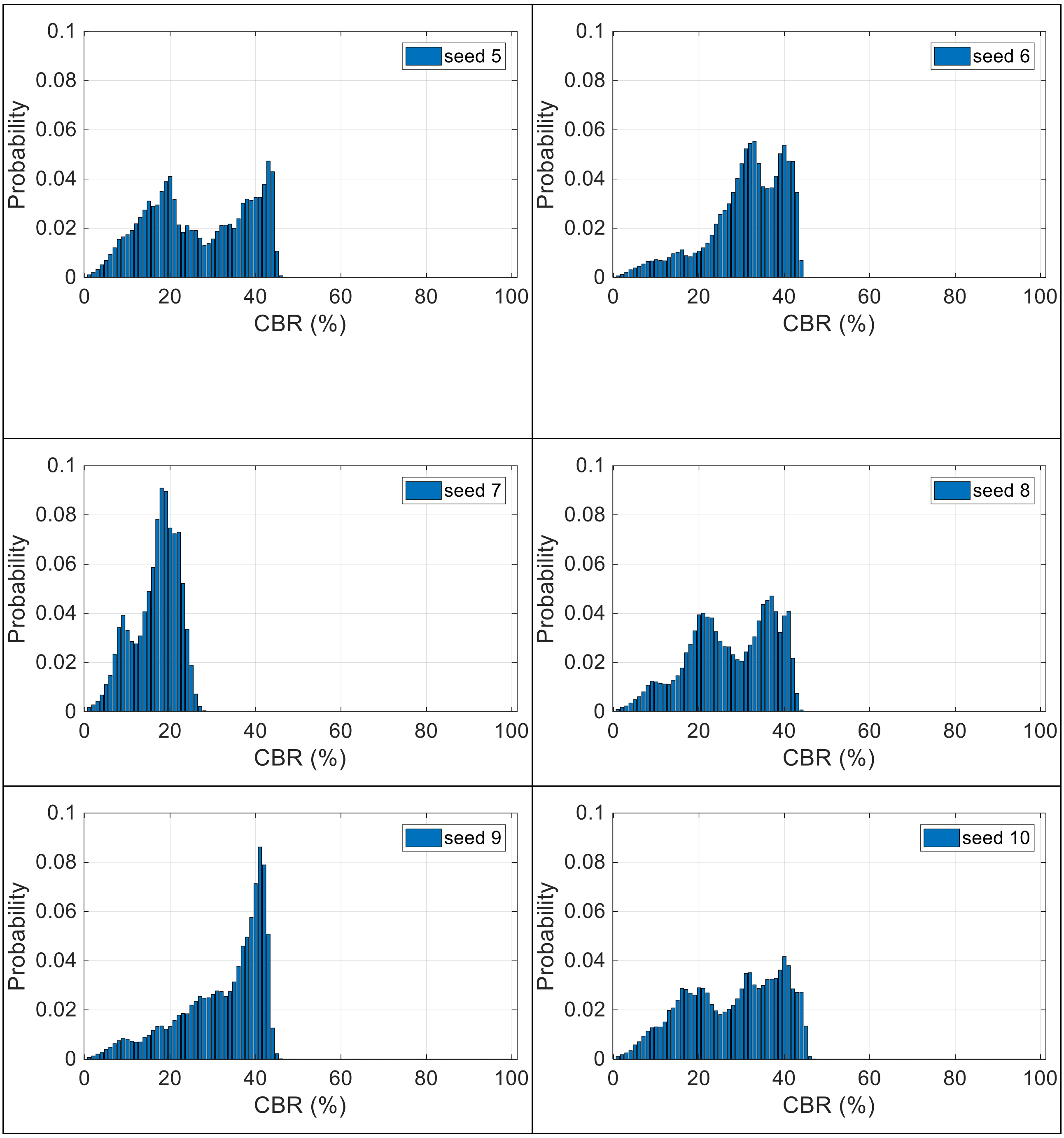


Figure 50: Channel busy ratio for LOS D mix 3 individual seeds.

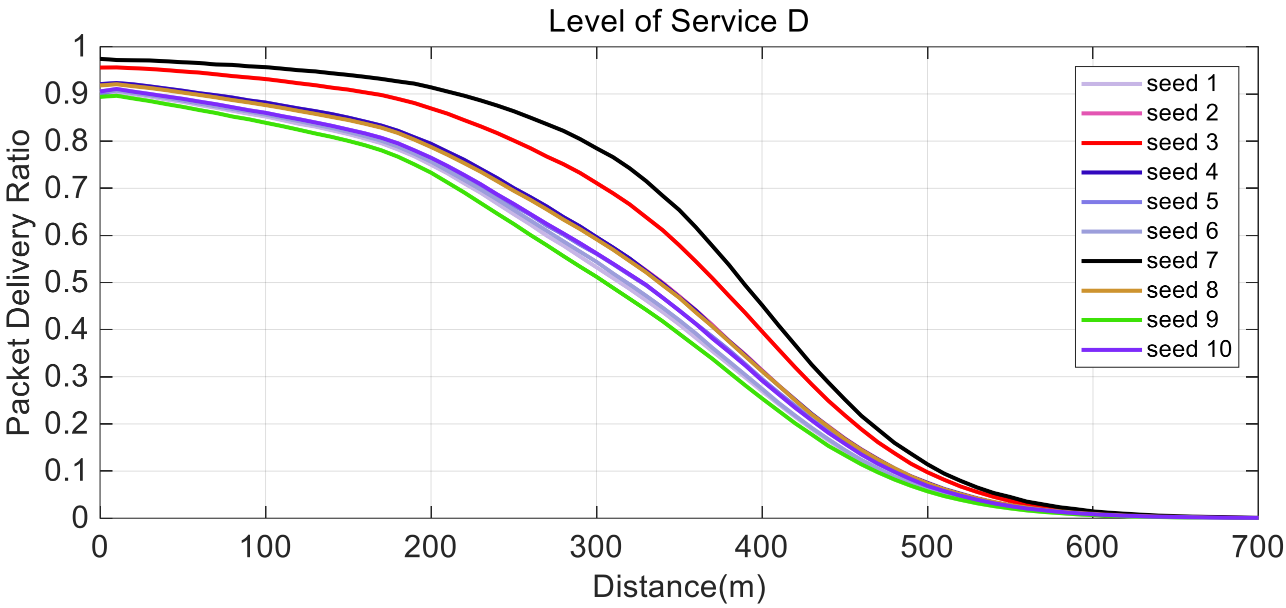


Figure 51: Packet delivery ratio for LOS D mix 3 individual seeds.

4.3.3 Discussion

The results obtained from the iTETRIS simulations, that encompassed both ideal and realistic communications, were found to be similar with the corresponding results (no communications) of Deliverable 4.2 [2] for the traffic conditions. The conducted analysis shows that the proposed traffic management measures in combination with realistic simulation of communication does not negatively influence the traffic behaviour or congestion. Looking at this result and considering that the communication range is limited in realistic V2X communication simulations (LightComm has no limits in communication range), on average all configurations achieved high PDR up to 300 m between transmitter and receiver. Beyond 300 m, the PDR tends to decrease due to propagation effects. Nevertheless, the traffic behaviour still stays stable for all configurations under realistic V2X communication simulations.

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

a) **Road-side infrastructure**
   - In the Use Case 2.3 the RSU location is fixed because this is the TLC controlling the intersection. Looking at the simulation results the communication radius of the TLC is sufficient. In the real world the RSU location is not always that evident just in a corner of an intersection. When deploying the use case in a real-world situation the communication radius, in combination with local speed limits, hindrance from obstacles (e.g., buildings, terrain characteristics, …) should be analysed. In some cases, additional transceivers could be necessary. A trade-off between deployment costs and effectiveness of the use case is desirable.

b) **Automated vehicle control**
   - Lane change/keep and MRM advice are received by virtually all CAVs to ensure increased efficiency and safety levels. However, it should be noted that immediate and complete compliance of CAVs with RSU advice 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 activates the use case. Therefore, a direct/wired connection to the physical RSU 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 use case. The current implementation takes this into account which adds to the robustness of the traffic management algorithm.

d) 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.
- In the simulation the SPATEM and ToC status information is handled by SUMO. In the real world the total channel load will increase. The total channel load and the frequency of retransmission of the infrastructure advices should be further studied to guarantee the correct reception of the advices while keeping the channel load as low as possible to avoid negatively impacting the performance of V2X communications.

4.4 Use Case 4.2: Safe spot in lane of blockage & lane change assistant

4.4.1 Introduction

In the second iteration we introduced several new elements regarding vehicle and management capabilities in Use Case 4.2 that significantly differentiate it from its first iteration variant. Firstly, we assumed that a portion of CAVs (CAVs_G1) will instantly execute TORs upon DENM reception, while the remaining portion (CAVs_G2) will cross the work zone in automated mode unless driving on the closed lane in its close proximity when dynamic TOR can take place. Secondly, the RSU can provide lane change/keep advice to CAVs/CVs upstream of the work zone to prevent inefficient merging operations at the lane drop location. Furthermore, cooperative lane changing between CAVs_G2 is possible to facilitate the advised lane changes from the RSU side. Finally, we assumed that, in the era of cooperative driving, digital infrastructure is expected to be more widespread, hence two RSUs are placed in the motorway network in accordance with Use Case 4.2 setup in [2]. Figure 52 depicts the locations of RSUs for both the urban and the motorway networks.

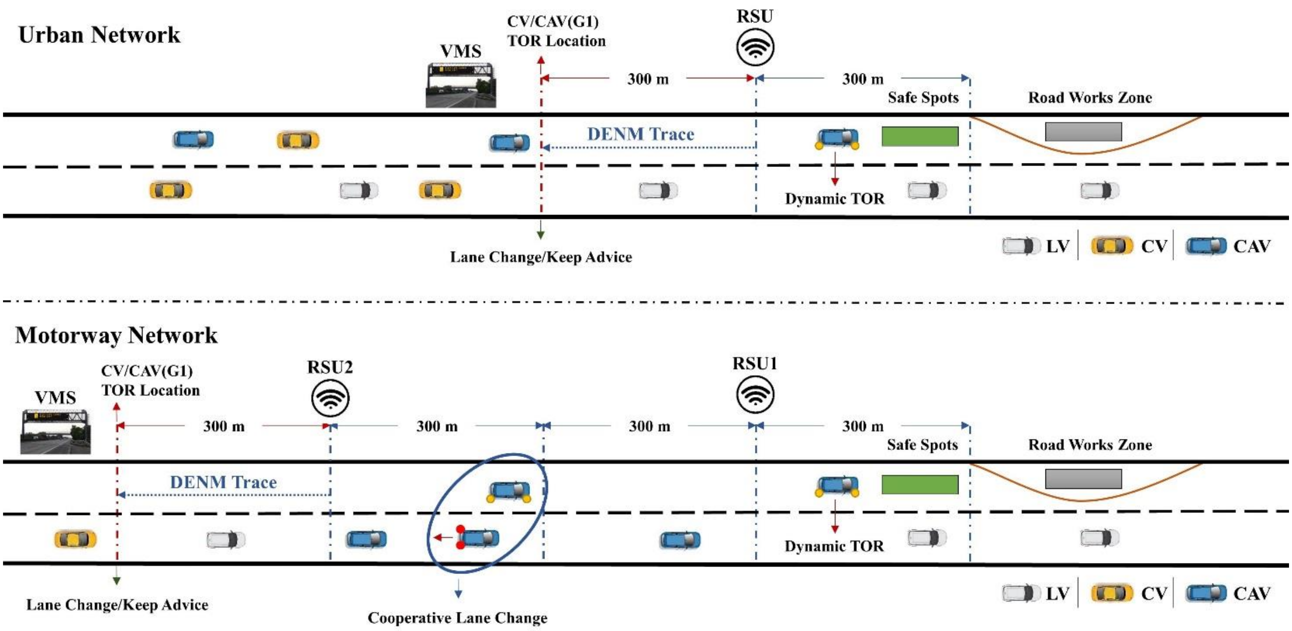


Figure 52: Location of RSUs for urban and motorway networks in Use Case 4.2.

The essential part of the communication protocol for Use Case 4.2 involves five types of messages exchanged between the RSU and the CAV and one type between CAVs. Three types are transmitted by the RSUs and three by the CAVs (see Figure 53):

- DENM containing road works info.
- MCM containing lane change/keep and MRM advice.
- MAPEM containing safe spot location.
- CAM containing current vehicle state.
- CPM containing collective perception information.
- MCM containing information for cooperative lane changing.

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, planned trajectories, etc.) collected via CAM, CPM, and MCM messages transmitted on regular intervals by the CAVs. Received CAMs, CPMs, and MCMs are centrally processed by the RSU (wired to the TMC) using the same traffic management program.

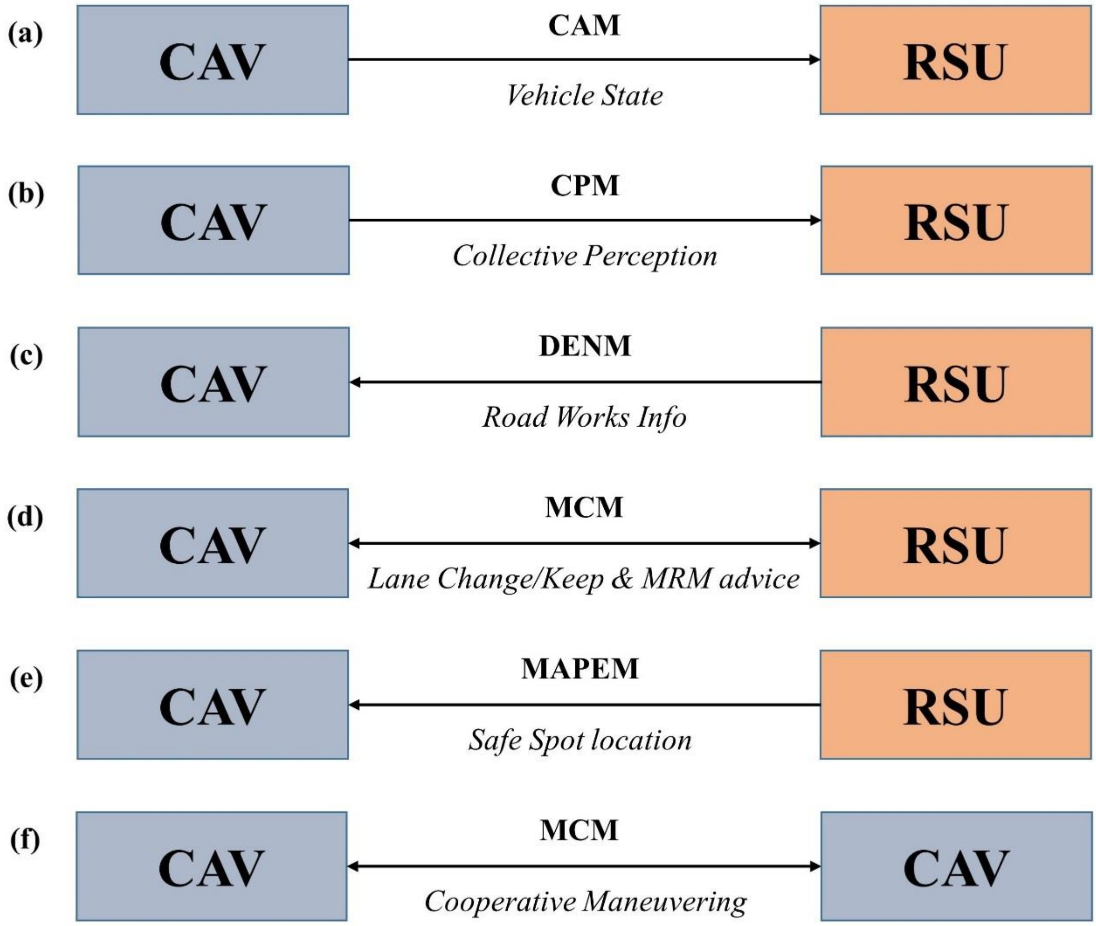


Figure 53: Exchange of messages in Use Case 4.2.

The RSU periodically broadcasts DENM messages informing CAVs (entering the communication range of the RSU) about the upcoming road works. Lane change/keep advice is explicitly provided to CAVs_G2 by the RSU via MCM messages according to their driving lane (assessed based on CAM and CPM messages sent by CAVs to the RSU) upon entering within communication range. 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. Finally, CAVs_G2 exchange MCMs including information about their planned and desired trajectories in order to execute cooperative lane change manoeuvres. For more information on the protocol, see also [9].

4.4.2 Results

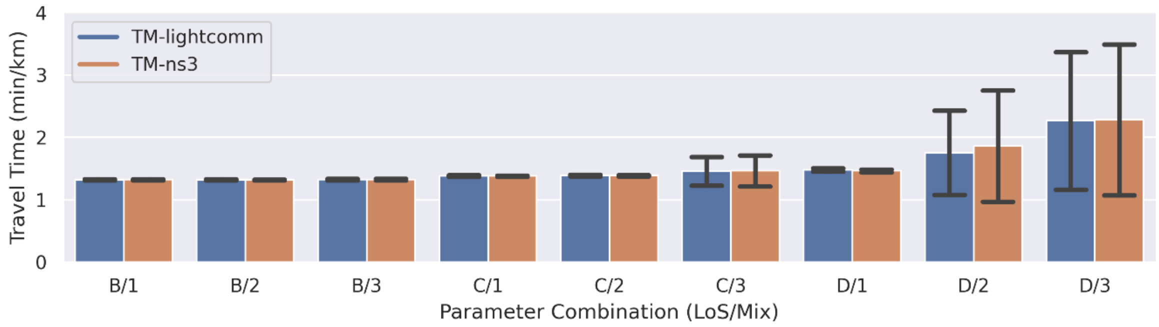
In the following, we present the simulation results (traffic and communication KPIs) obtained for this use case (urban and motorway traffic conditions). The main goal of the assessment is to determine the robustness of the traffic management procedures with respect to the inclusion of realistic communication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

Traffic

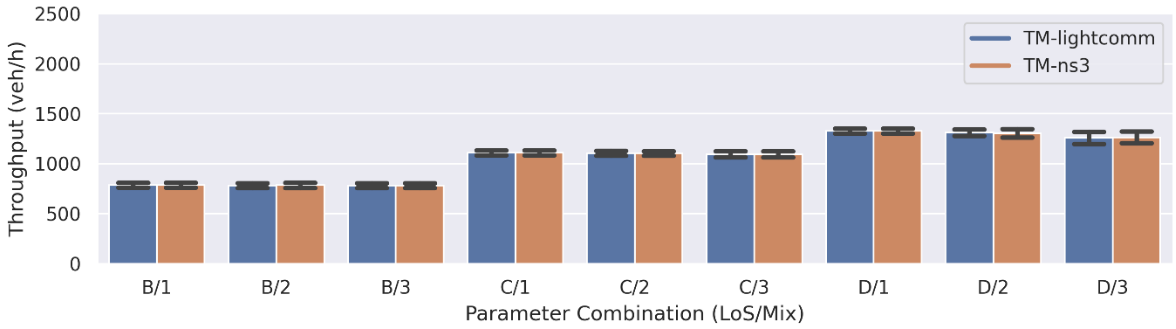
Traffic efficiency is assessed based on average network statistics (travel time and throughput bar plots) and spatio-temporal plots of speed and flow (obtained from simulated detector raw output). On the contrary, traffic safety and environmental impacts are assessed explicitly based on network-wide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

Figure 54 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. 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 55). This supports the claim that the V2X communications do not impact the efficiency of the traffic management procedures for this use case in urban traffic conditions.



(a)



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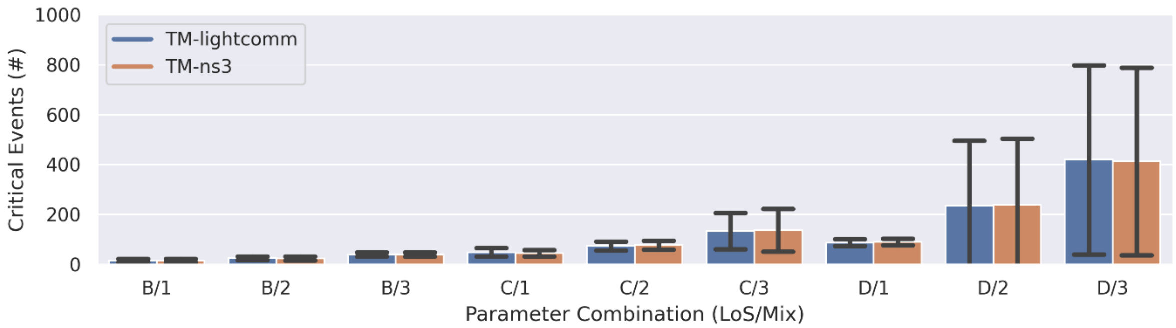
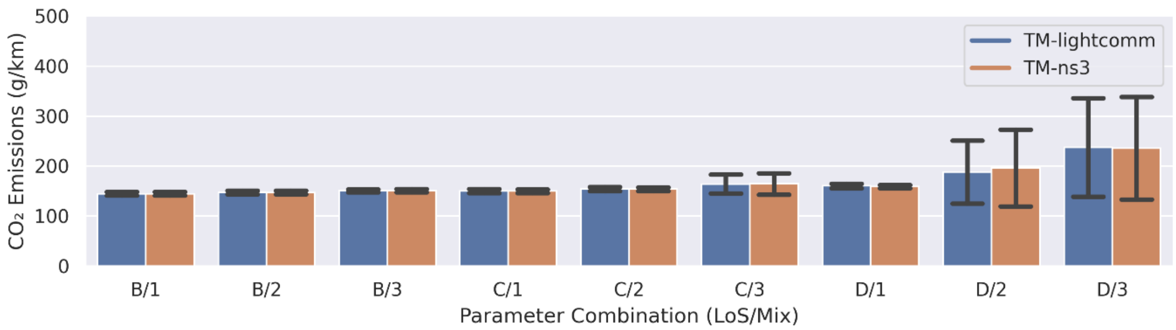


(c)



(d)

Figure 54: Average network statistics for Use Case 4.2 (urban network). Error bars show the standard deviation among ten replications over one-hour simulation time for the corresponding parameter combination.

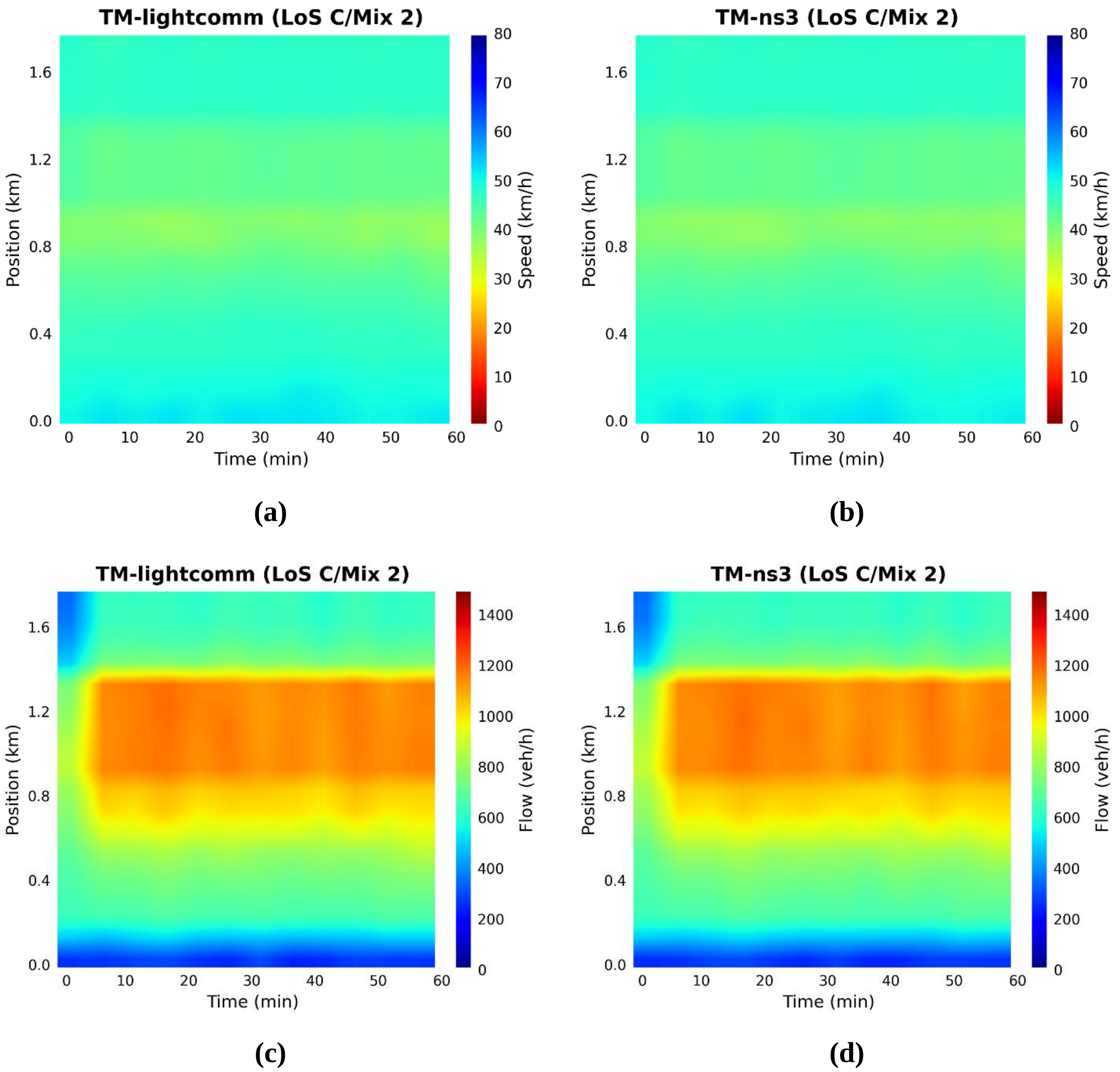
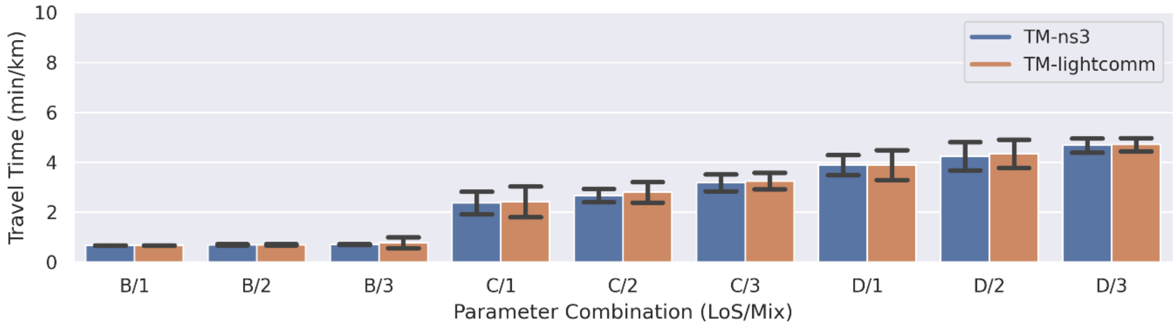


Figure 55: Average spatio-temporal plots for measured speeds (upper row) and flows (bottom row) for Use Case 4.2 (urban network, LOS C, vehicle mix 2). The left column corresponds to ideal communications and the right column to realistic communications.

Average local and network simulation results for motorway traffic conditions (Figure 56 and Figure 57) indicate that there are no observable differences between ideal (i.e. LightComm) and realistic (i.e. ns-3) communications scenarios either. Mean values and standard deviation of network-wide statistics are similar, while average traffic flow and speed patterns match along the motorway network. Hence, V2X communications do not impact the efficiency of the traffic management measures in motorway traffic conditions as well.



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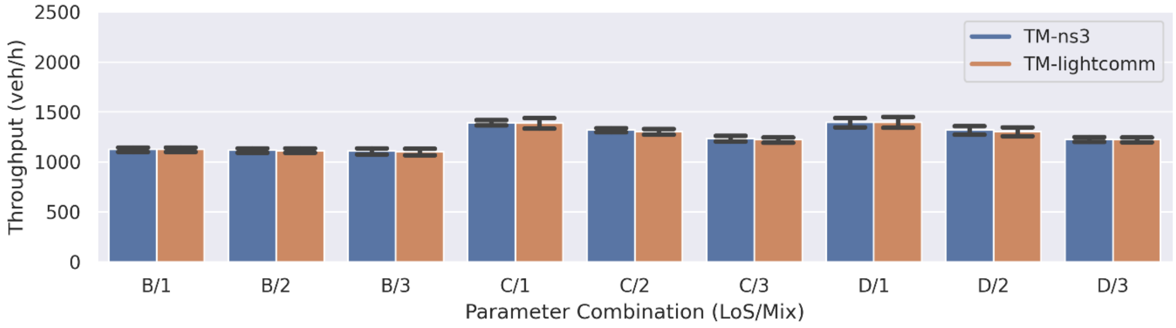

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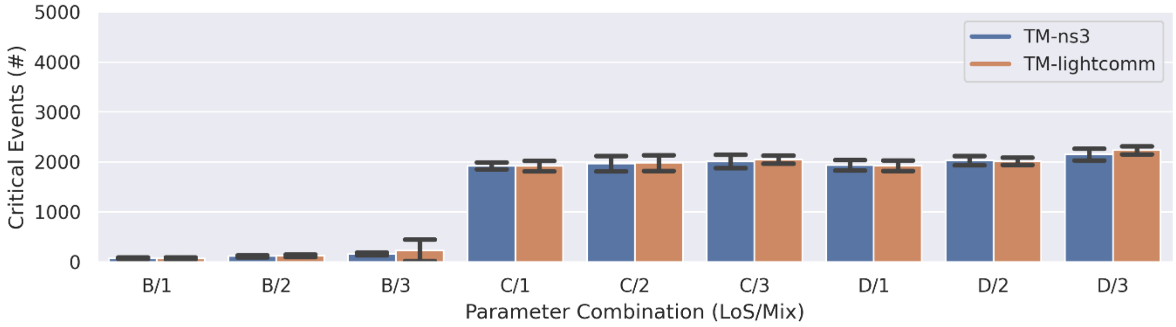

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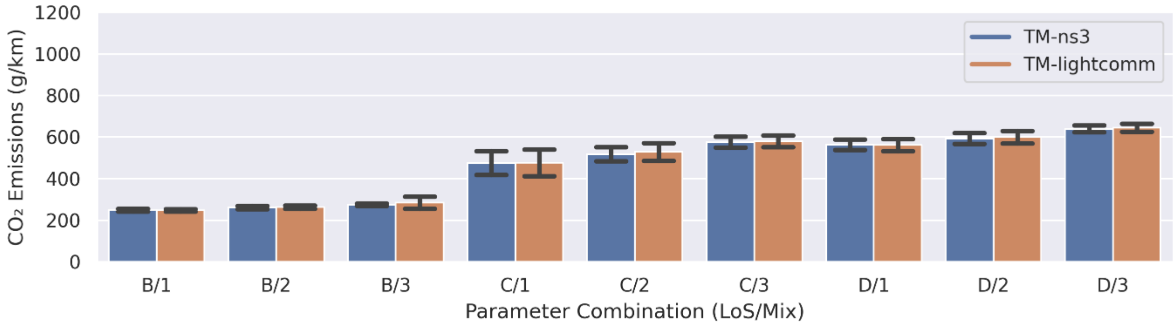


(d)

Figure 56: Average network statistics for Use Case 4.2 (motorway network). Error bars show the standard deviation among ten replications over one-hour simulation time for the corresponding parameter combination.

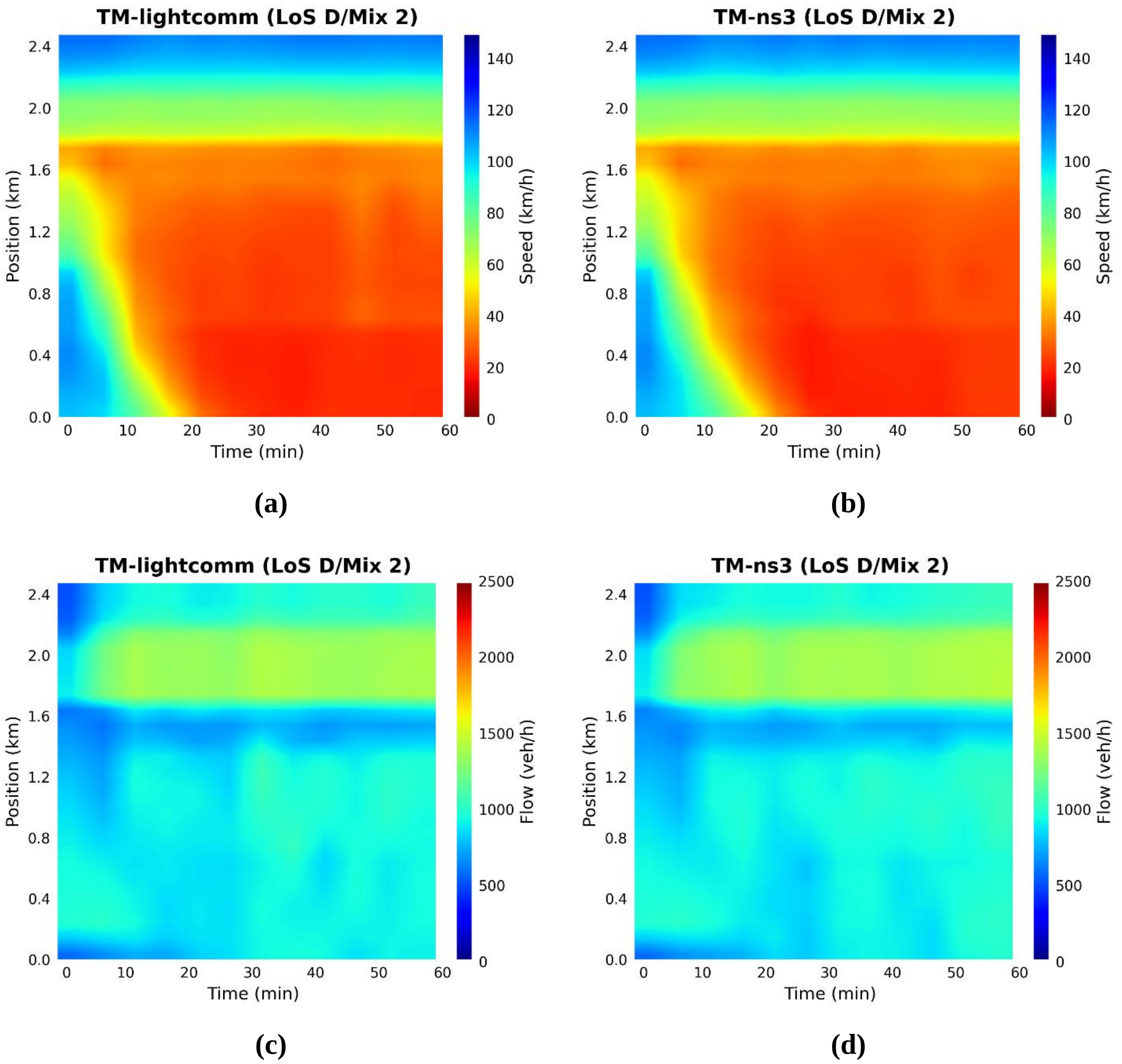


Figure 57: Average spatio-temporal plots for measured speeds (upper row) and flows (bottom row) for Use Case 4.2 (motorway network, LOS D, vehicle mix 2). The left column corresponds to ideal communications and the right column to realistic communications.

Communication

This section evaluates the impact of the traffic management measures of Use Case 4.2 in the performance of V2X communications for both the urban and motorway scenarios.

First, we analysed the communication performance achieved in the urban scenario. We computed the Channel Busy Ratio (CBR) which is a measure of the channel load and is 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 25 summarises the CBR for the different levels of service (LOS) and traffic mixes evaluated in the urban scenario of Use Case 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 12 %. These channel load levels are considered adequate for the deployment of the traffic management measures implemented for this scenario. Congestion control protocols that reduce the channel load to prevent channel congestion would only be activated at higher channel load levels. This indicates that the interference level in the urban scenario is low and a relatively low number of packets will be lost due to collision.

Table 25: Channel Busy Ratios for Use Case 4.2 in urban scenario.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	2.90 %	4.79 %	7.54 %
LOS C	4.18 %	6.96 %	12.50 %
LOS D	5.19 %	10.73 %	20.81 %

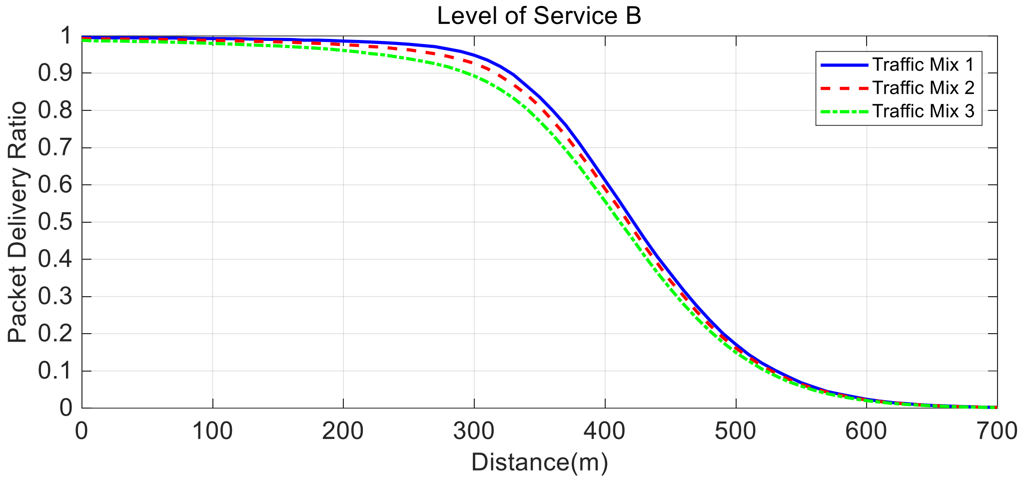
The observed low CBR will improve the successful reception of packets and reduce the latency. Table 26 shows the average latency measured in the urban scenario of Use Case 4.2 for all the different levels of service and traffic mixes. The latency is defined as the time elapsed between the transmission and the reception of a packet 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 considers successfully received messages. We can observe from Table 26 that the average measured latency is around 1.3 ms for all the combinations of traffic mix and LOS. This time suffices for the successful implementation of the traffic management measures defined in Use Case 4.2 for the urban scenario. Also, the observed latency values match with the existing ones available in the literature for relatively low CBR levels [16].

Table 26: Latencies for Use Case 4.2 in urban scenario.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	0.61 ms	0.63 ms	0.68 ms
LOS C	0.62 ms	0.66 ms	0.82 ms
LOS D	0.63 ms	0.76 ms	1.35 ms

Figure 58 shows the Packet Delivery Ratio (PDR) of the different levels of services and traffic mixes evaluated in the urban scenario of Use Case 4.2. The Packet Delivery Ratio (PDR) defined as the probability of successfully receiving a message as a function of the distance between the transmitting and receiving vehicles. The results reported in Figure 58 show that the PDR decreases with the increasing number of connected 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 increase the interference and it is more likely that packet collisions occur. 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. This is because the probability of successful reception of at least one message received by vehicles within 300m from the RSU and other connected vehicles is very high due to the higher PDR reported within this distance. In particular, the results obtained show that, in the worst-case scenario (LOS D and traffic mix 3), a

PDR higher than 0.9 can be achieved at distances up to 100 m. This distance is increased to 200 m for LOS C and 300 m for LOS B, for the same traffic mix.



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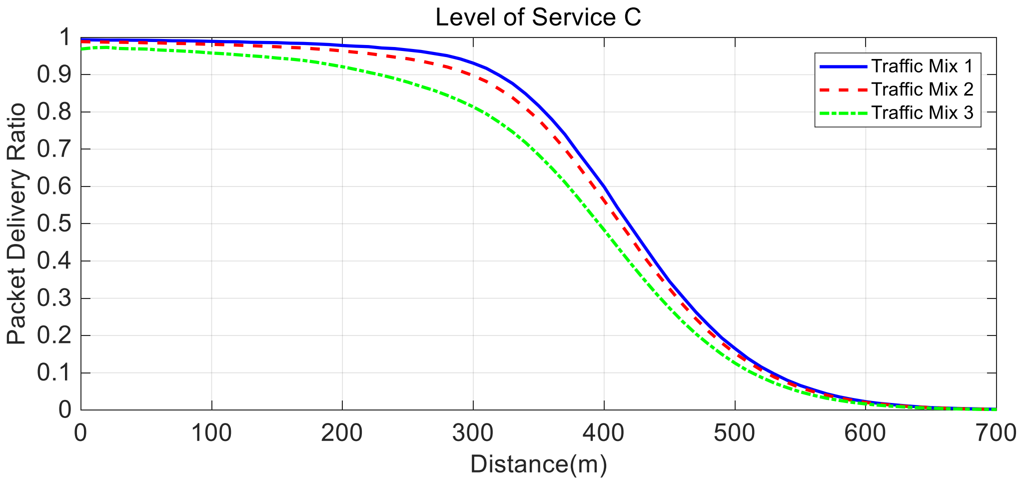

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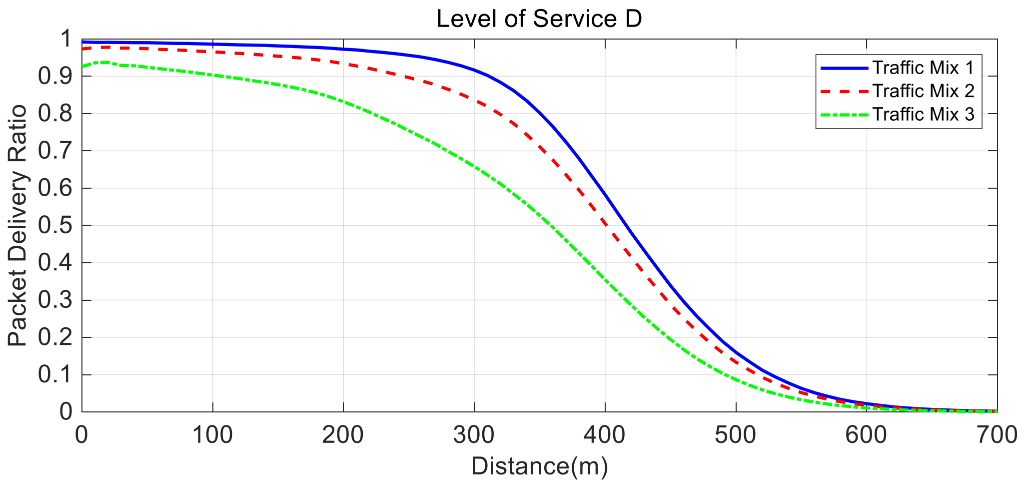


(c)

Figure 58: Packet Delivery Ratio for Use Case 4.2 in urban scenario.

The overall analysis of the communications KPIs for the urban scenarios shows that the reliability of the V2X communications is in principle sufficient to satisfy the communication needs of the traffic management measures of Use Case 4.2.

The obtained results show similar trends in the performance of the V2X communications for the motorway scenario than for the urban scenario, but with higher channel load levels. Table 27 summarises the CBR for the different levels of service and traffic mixes evaluated in the motorway scenario of Use Case 4.2. As it can be observed, in the motorway scenario the measured CBR can reach up to nearly 31 %. Still, these CBR levels are below the maximum threshold of 60 % typically considered by congestion control protocols. As expected, the CBR increases with the level of service and traffic mix. Consequently, Table 27 shows the highest CBR levels for the LOS C and LOC D with traffic mix 3 configuration. However, the measured CBR levels for all the evaluated configuration parameters show that the interference level in the motorway scenario is low and a relatively low number of packets will be lost due to collision.

Table 27: Channel Busy Ratio for Use Case 4.2 in motorway scenario.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	2.69	4.57	7.19
LOS C	11.39	20.60	30.94
LOS D	13.11	21.09	31.53

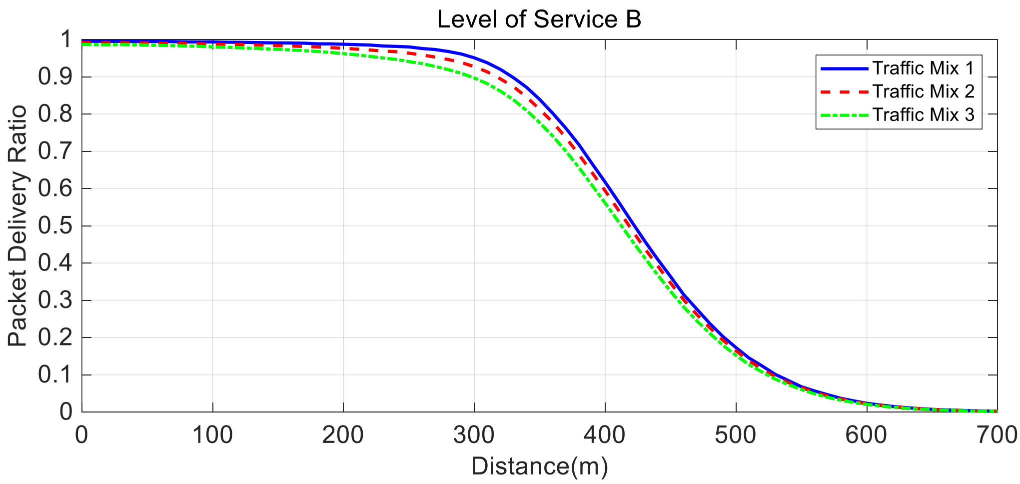
Table 28: Latencies for Use Case 4.2 in motorway scenario.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	0.65 ms	0.68 ms	0.72 ms
LOS C	0.72 ms	1.04 ms	2.03 ms
LOS D	0.74 ms	1.01 ms	2.0 ms

The observed low CBR will improve the successful reception of packets and reduce the latency. Table 28 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 Use Case 4.2, as vehicles have enough time to receive message and execute the corresponding manoeuvre in a safe and efficient way.

Finally, Figure 59 shows the PDR obtained in the simulation of the motorway scenario of Use Case 4.2 for the three different levels of service with different traffic mixes. The reported PDR represents the average of all V2X transmissions occurring during the simulations. As expected, increasing the number of vehicles with V2X capabilities results in a slight decrease of the PDR at the same distance due to the increased interferences and probability of packet collisions. 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. 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. This is the case because vehicles can start receiving messages at distances beyond 500m, although with low probability. As they approach to an RSU within 300m, this probability increases. Since there are two RSUs placed in the motorway scenario, the probability that vehicles receive at least one traffic related message before reaching 300m from every RSU is therefore high, even in the scenario with LOS D and traffic mix 3, despite the low PDR.



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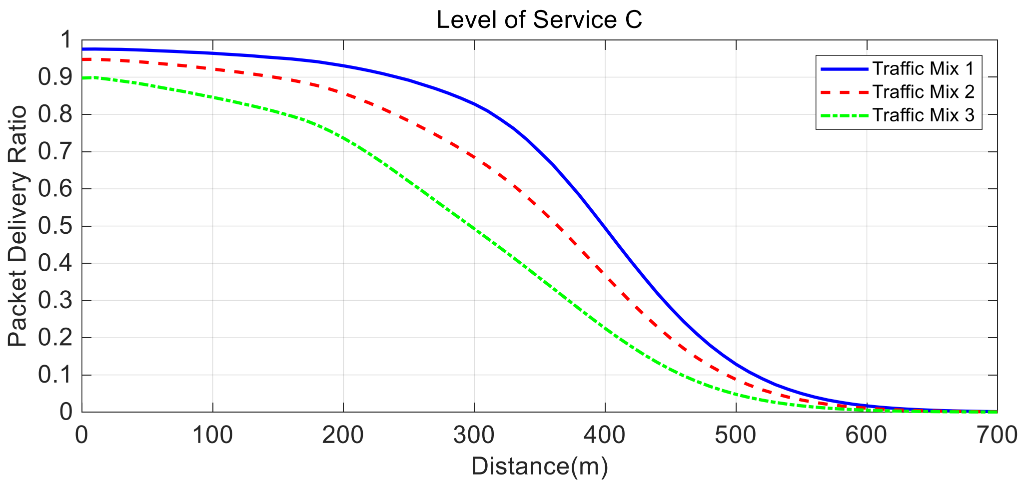

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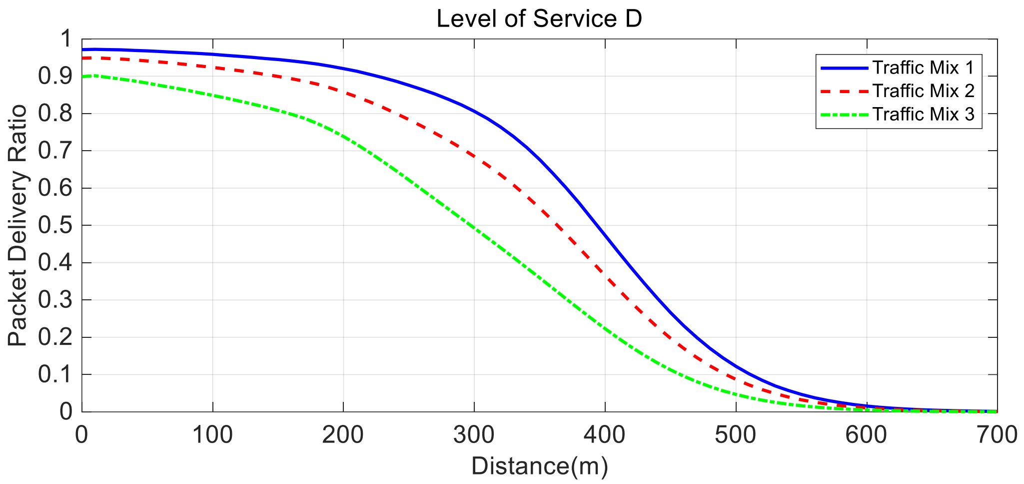


(c)

Figure 59: Packet Delivery Ratio for Use Case 4.2 in motorway scenario.

The overall analysis of the communications KPIs for the motorway scenarios shows that the reliability of the V2X communications is in principle sufficient to satisfy the communication needs of the successful traffic management measures of Use Case 4.2.

4.4.3 Discussion

The results obtained from the iTETRIS simulations, that encompassed both ideal and realistic communications, were found to be similar with the corresponding results (no communications) of Deliverable 4.2 [2] for both urban and motorway traffic conditions. In contrast to relevant simulations in the first project iteration (cf. Section 3.4), guidance to safe spot was successful in the case of motorway conditions (every simulation run in the second project iteration). Thus, the conducted analysis has shown that the transmission of the necessary messages to execute the traffic management measures of the TransAID Service 4 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 use case, 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**
   - Lane change/keep and MRM advice are received by virtually all CAVs to ensure increased efficiency and safety levels at the lane drop location. However, it should be noted that immediate and complete compliance of CAVs with RSU advice 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 use case. The current implementation takes this into account which adds to the robustness of the traffic management algorithm.

d) 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.
- 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.

4.5 Use Case 4.1 + 5.1: Distributed safe spots along an urban corridor

4.5.1 Introduction

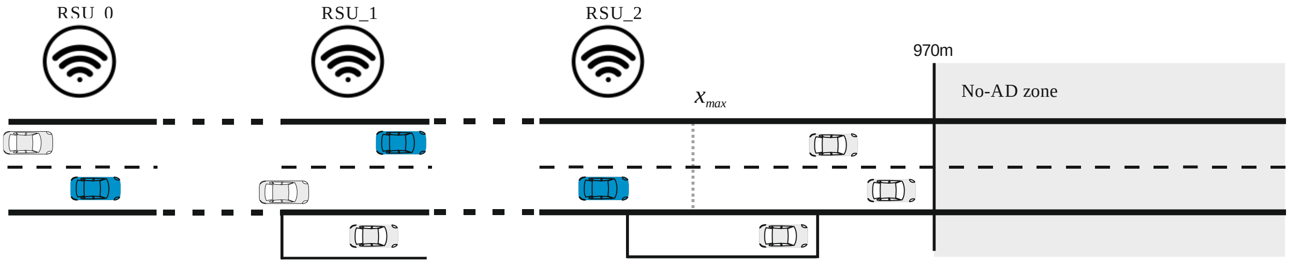


Figure 60: Schematic representation of Use Case 4.1 + 5.1.

In this use case, we consider a road section with an upcoming No-AD zone, where automatic driving is prohibited, as well as road-side parking spots beside the road stretch approaching the No-AD zone (cf. Figure 60). Road participants are comprised of LVs, heavy and light trucks, CVs, and CAVs, where some of the CAVs perform an MRM action. This baseline case, as discussed in D3.1 [1], is prone to heavy traffic flow disruption due to the accumulation of ToCs just before the No-AD zone as well as due to the MRM actions performed by some CAVs. To alleviate these problems, a traffic management algorithm was proposed and detailed in D4.2 [2], which mainly consists of two services:

- Service 5, which is a heuristic for distributing TORs within the controlled area leading up to the No-AD zone.
- Service 4, a heuristic for assessing and targeting available safe spots, i.e., empty parking spots, such that CAVs performing a ToC can safely do so while parking.

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 use case as ToC and safe spot 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 970m-long road segment approaching the No-AD zone (see Figure 60). Their locations are given in Table 29.

Table 29: Location of RSUs in Use Case 4.1 + 5.1.

RSU ID	Distance from entry point
“RSU_0”	200 m
“RSU_1”	500 m
“RSU_2”	800 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 use case 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.

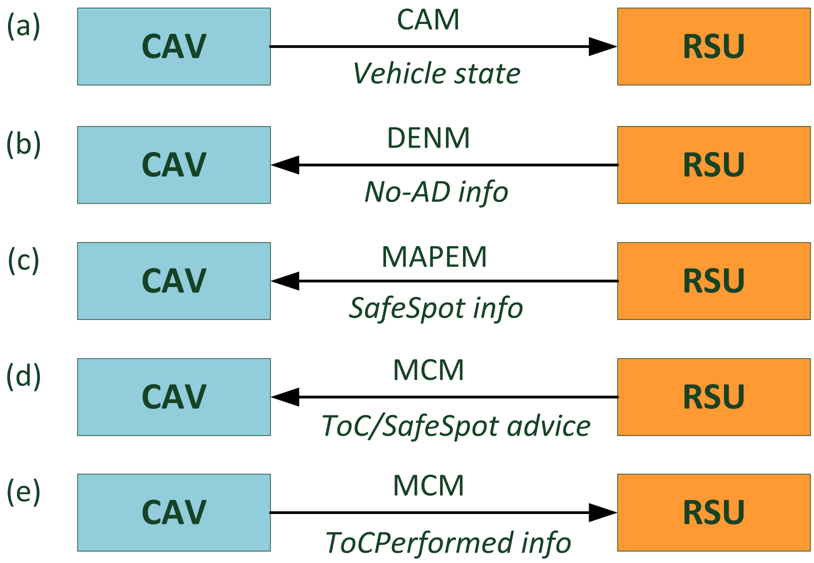


Figure 61: Communication message types exchanged in Use Case 4.1 + 5.1.

The essential parts of the communication protocol for Service 4 + 5 involve five types of message exchange of which three are transmitted by the RSUs: a DENM containing the No-AD info, a MAPEM containing the SafeSpot info, and MCMs containing a ToC advice and a SafeSpot advice, respectively. The remaining two message exchanges originate from the CAVs, namely CAMs containing the current vehicle state as well as an MCM containing the ToCPerformed info. For an overview of these messages, see Figure 61.

The RSUs send ToC and SafeSpot advices to individual vehicles when they are close to the assigned ToC position. Additionally, No-AD and SafeSpot 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 and MCMs are centrally processed for all RSUs by the same traffic management program.

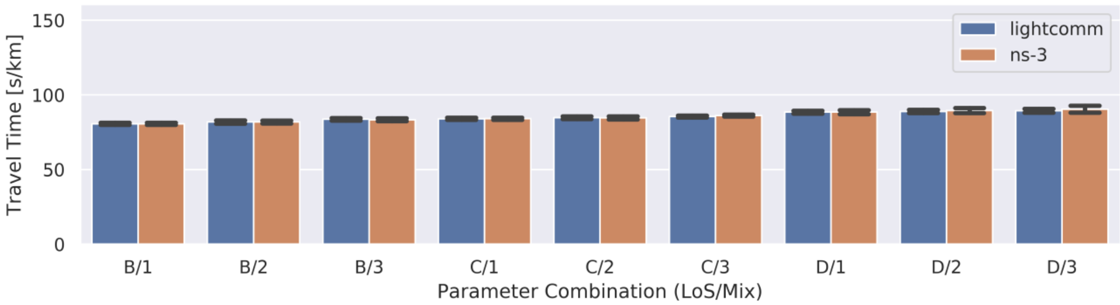
If a CAV receives a No-AD info, it will, *in any case*, perform a transition before entering the No-AD zone, regardless of whether a subsequent ToC advice was received. We assume that only the reception of a ToC advice may cause the vehicle to induce a transition earlier than the latest possible point x_{max} for starting a transition autonomously (see Figure 60), 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 perform an MRM action. For more information on the protocol, see also [9].

4.5.2 Results

In this section, we present and describe the simulation results obtained for this use case. 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 use case 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 dynamics, traffic safety, and environmental impact, quantified with the network-wide traffic KPIs “travel time”, “throughput” and “lane changes”, “critical events”, and “CO_2 emissions”, respectively (cf. [14]). Additionally, we inspected the number of TORs and MRMs, which are specific to TransAID.



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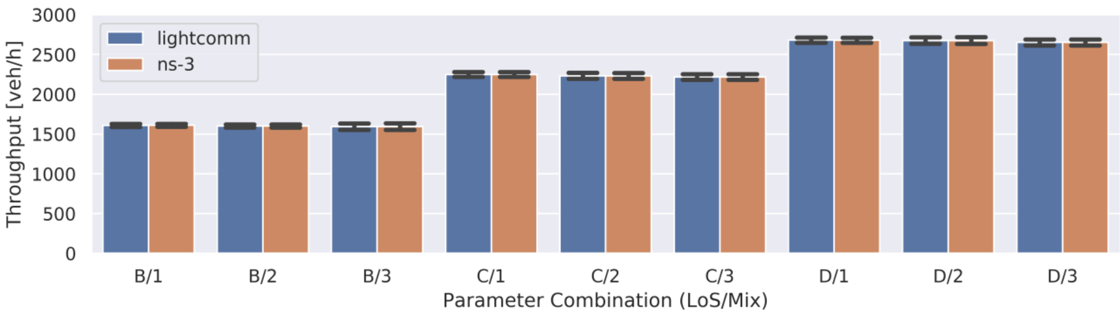

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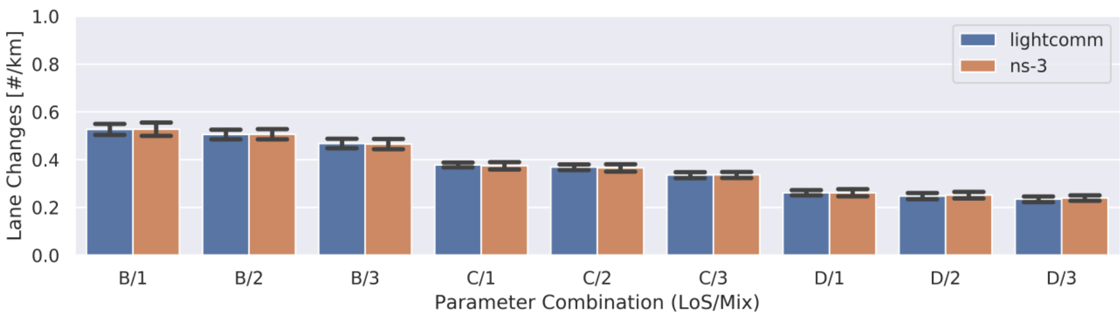

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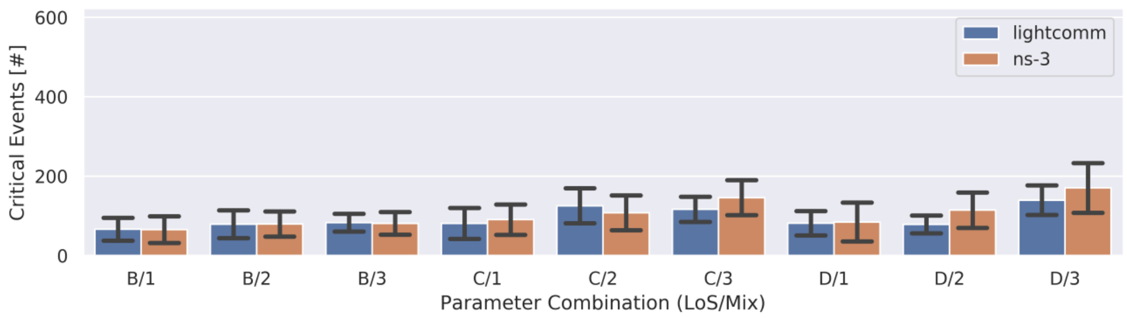

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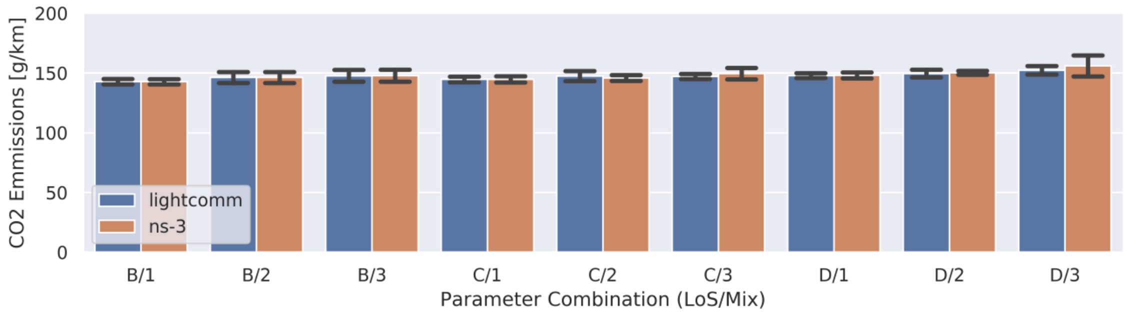

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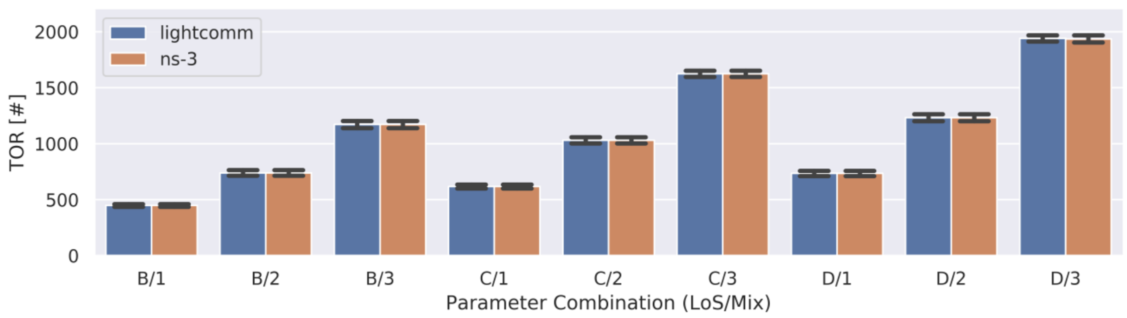

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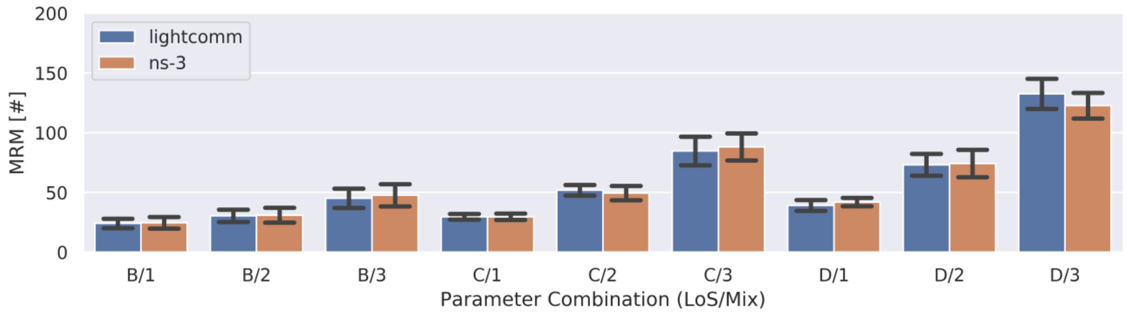


(g)

Figure 62: Network-wide simulation results for Use Case 4.1 + 5.1. Error bars show the standard deviation among ten replications over one-hour simulation time for the corresponding parameter combination.

Figure 62 summarises the network-wide simulation results for this use case. When comparing these results to the ones presented in D4.2 [2], where baseline and traffic management Use Case 4.1 + 5.1 without communication where evaluated, we can verify that all - except MRM - KPI results for LightComm, i.e., the “ideal” communication, are comparable to traffic management Use Case 4.1 + 5.1 results without any communication. The exception is the number of MRMs (cf. Figure 62(g)), where, for all parameter combinations, we have significantly lower total numbers compared to results in D4.2. However, we can verify the same trend here, i.e., the number of MRMs increases with the level of service and traffic mix. Moreover, the lower number of MRMs can be attributed to the way the new traffic management algorithm adjusts the ToC lead time (cf. D4.2, Section 3.2.5.3.5).

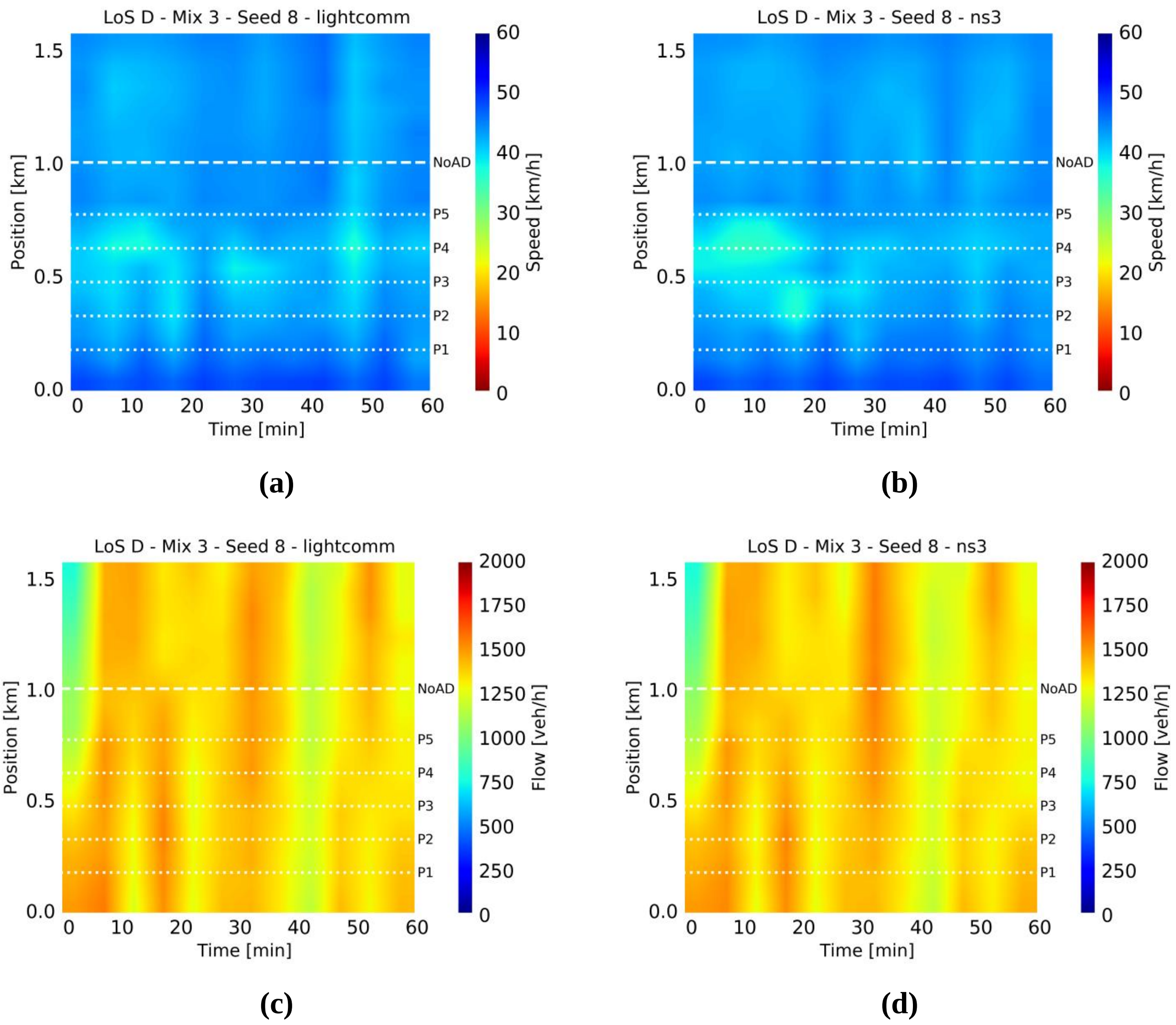


Figure 63: Example spatio-temporal plots visualising KPIs speed (a, b) and flow (c, d), respectively, for Use Case 4.1 + 5.1. For both KPIs, ideal (a, c) and realistic (b, d) communication results are shown side-to-side for easier comparison.

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 62). 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 63) 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. The CBR is defined as the percentage of time that the channel is sensed as busy. Table 30 shows the average CBR for all the vehicles in the simulation. The results are reported for all combinations of use case parameters, i.e. levels of service (LOS B, C and D) and traffic mixes (1, 2, 3). The obtained results show that for all the combinations of use case parameters, the CBR is around or below 32 % (for the scenario with LOS D 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 32 % of the time. These channel load levels are considered adequate for the deployment of the traffic management measures implemented for this use case. Congestion control protocols that reduce the channel load to prevent channel congestion would only be activated at higher channel load levels. This indicates that the interference level is low and a relatively low number of packets will be lost due to collision.

Table 30: Channel Busy Ratio for Use Case 4.1+5.1.

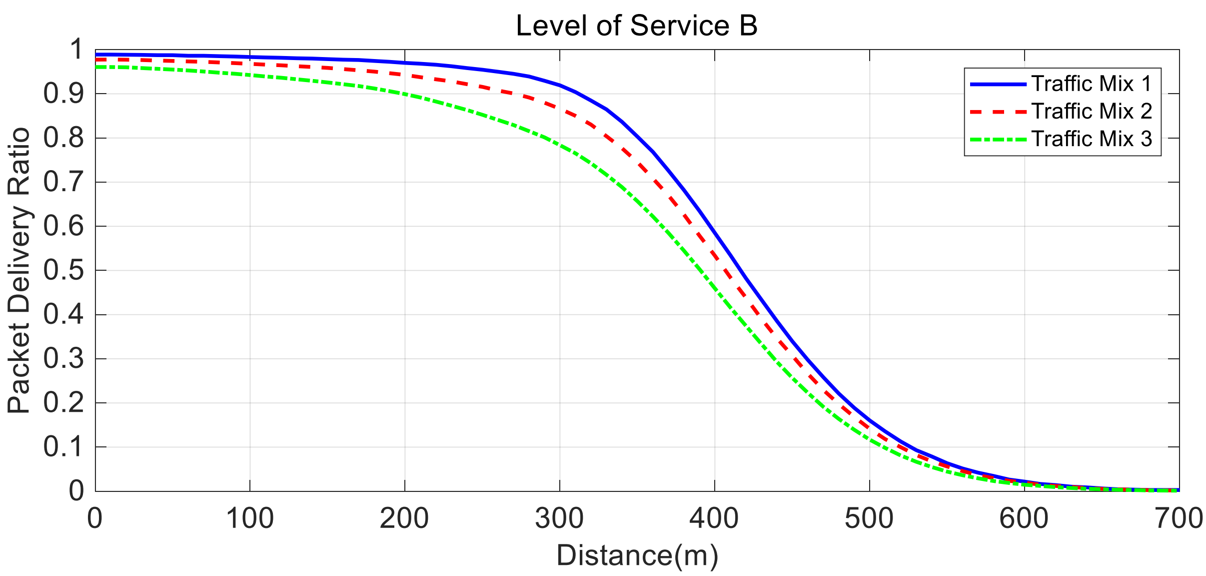
	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	6.95 %	12.42 %	19.96 %
LOS C	10.37 %	18.02 %	27.24 %
LOS D	12.62 %	21.61 %	32.41 %

The observed low percentage of CBR will improve the successful reception of packets and reduce the latency. Table 31 shows the average latency of the V2X communications performed during the simulations of Use Case 4.1+5.1. 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 use case parameters is around or below 2.5 ms. These significant lower latency values guarantee that the vehicles will receive the traffic management measures with enough time to safely execute the required manoeuvres. Also, the observed latency values match with the existing ones available in the literature for relatively low CBR levels [16].

Table 31: Latencies for Use Case 4.1+5.1.

	Traffic mix 1	Traffic mix 2	Traffic mix 3
LOS B	1.03 ms	1.18 ms	1.47 ms
LOS C	1.12 ms	1.38 ms	1.99 ms
LOS D	1.18 ms	1.54 ms	2.46 ms

Finally, Figure 64 shows the PDR for the three different levels of service with different traffic mixes. 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 64 also includes the results obtained for traffic mixes in order to analyse the effects of increasing the number of CVs and CAVs in the use case. 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 use case, the traffic results reported above show that the V2X communications do not negatively impact the traffic KPIs. This is the case because vehicles can start receiving messages from an RSU at distances beyond 300m, although with low probability. As they approach to the next RSU, this probability of receiving the packet increases significantly thanks to the deployment of multiple RSUs. Therefore, the probability that at least one message is received before reaching 300m is high, even in the scenario with LOS D and traffic mix 3, despite the reported low PDR. In particular, the results obtained show that, in the worst-case scenario of traffic mix 3, a PDR higher than 0.9 can be achieved at distances up to 100 m for LOS C and LOS D. This distance is increased to 200 m for LOS B for the same traffic mix 3.



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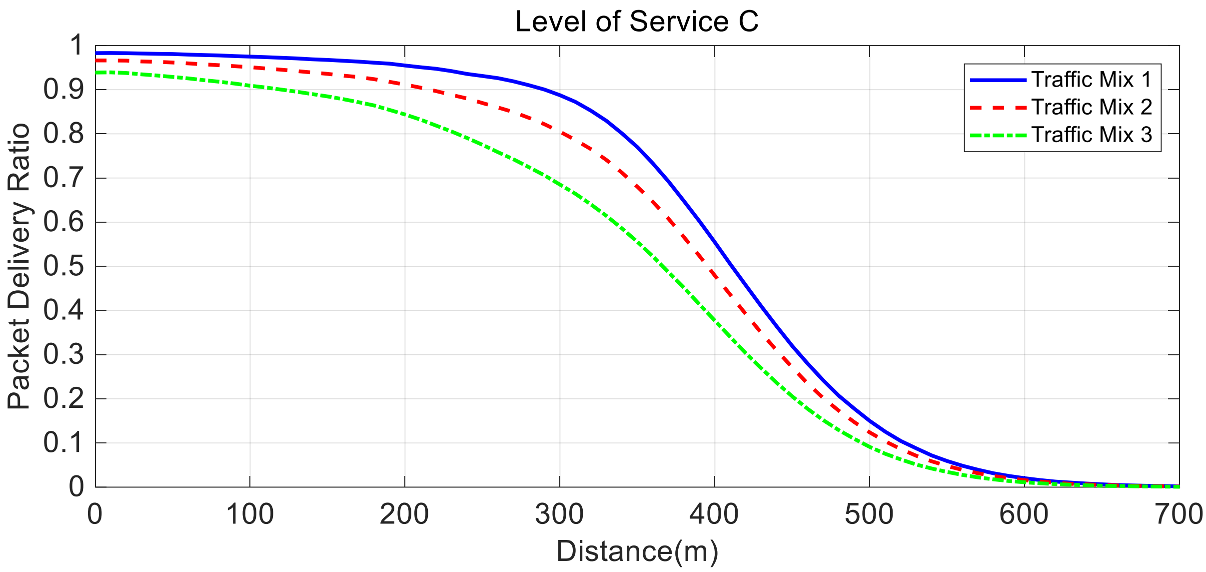

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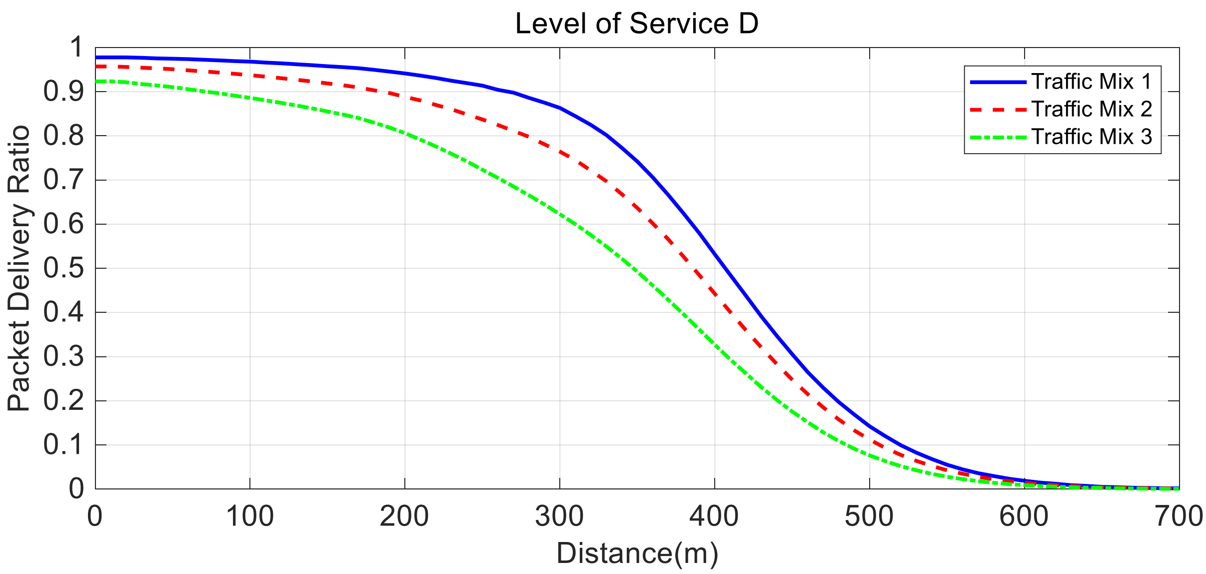

(c)

Figure 64: Packet Delivery Ratio for Use Case 4.1+5.1.

The overall analysis of the communications KPIs shows that the reliability of the V2X communications is in principle sufficient to satisfy the communication needs of the traffic management measures of Use Case 4.1+5.1.

4.5.3 Discussion

The simulation results obtained after implementing the use case and traffic management measures within the iTETRIS framework have confirmed the essential results of Deliverable 4.2 [2], i.e., the proposed traffic management algorithm combining Services 4 (safe spot assistance) and 5 (TOR distribution) can indeed benefit the traffic flow and improve traffic safety. In contrast to Use Case 5.1 (cf. Section 3.5), the comparison of simulations results with ideal and realistic communication has shown no significant sensitivity of traffic KPIs to communication errors. However, this observation is somewhat misleading since the road segment approaching the No-AD zone is much shorter and the placement of RSUs is, therefore, much denser in Use Case 4.1+5.1, while the communication radius is comparable. This leads to a lower message loss.

The conducted communication analysis has additionally shown that the transmission of the necessary messages to execute the traffic management measures of TransAID Services 4 and 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 use case, 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 use case. 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.
   - 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.

4.6 Conclusion

In a similar fashion to the first iteration, all five TransAID use cases considered in the project's second iteration including the proposed traffic management measures were simulated and evaluated with focus on the impact of realistic V2X communications. For this purpose, the use cases were ported to the iTETRIS platform where feasible (see Use Case 2.1 in Section 4.2 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 use cases 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 Use Cases 1.3, 2.1, 4.2, and 4.1+5.1 have shown that these use cases are not adversely impacted by realistic V2X communication. In case of Use Case 2.3, a few results were singled out to be statistical outliers but, overall, the same conclusion can be drawn for this use case. Furthermore, Use Cases 4.2 and 4.1+5.1, in which traffic management procedures from the first iteration were complemented and/or improved upon, exhibited no significant impact of realistic communication on traffic KPIs, which suggests that the sensitivity of the respective traffic management measures to realistic V2X communication, that was identified in the first iteration, has at least been decreased. Similarly, the simulations for Use Case 1.3 with realistic communication did not have any impact on traffic KPIs.

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 (which even led to intractable computation times for Use Case 1.3 LOS D). Despite this, a lot of effort has been successfully made to optimise the overall simulation runtime, especially for higher density scenarios. Even with higher levels of service and traffic mixes compared to the first iteration, simulation runtimes for all use cases were at least manageable to the degree that these could be run to completion, in contrast to the case of Use Case 3.1 from the first iteration where the LOS D (and to a lesser extent LOS C) kept causing crashes.

In conclusion, the performance evaluation of the considered use cases and parameter combinations has shown the following, which still holds true as in the first iteration:

- 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.

5 Recommendations for the Real-world Prototype

5.1 Introduction

The aim of this section is to provide recommendations, based on the results of the integrated simulations (or “the virtual prototypes”, see Sections 3 & 4), 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 use cases’ “Discussion” subsections of Sections 3 & 4.

5.2 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.

5.3 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.

5.4 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.

5.5 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 Manoeuvre Coordination Service allowing the inclusion of RSU 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.

5.6 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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Appendix A: Step-by-Step Guide for Creating an iTETRIS Application

In order to perform an iTETRIS simulation, multiple configuration files for the different system components are required. These are XML formatted files and contain dedicated configuration parameters for every section that composes the iTETRIS platform. Figure 65 shows the hierarchy of those needed files. A detailed description of each file can be found in [19].

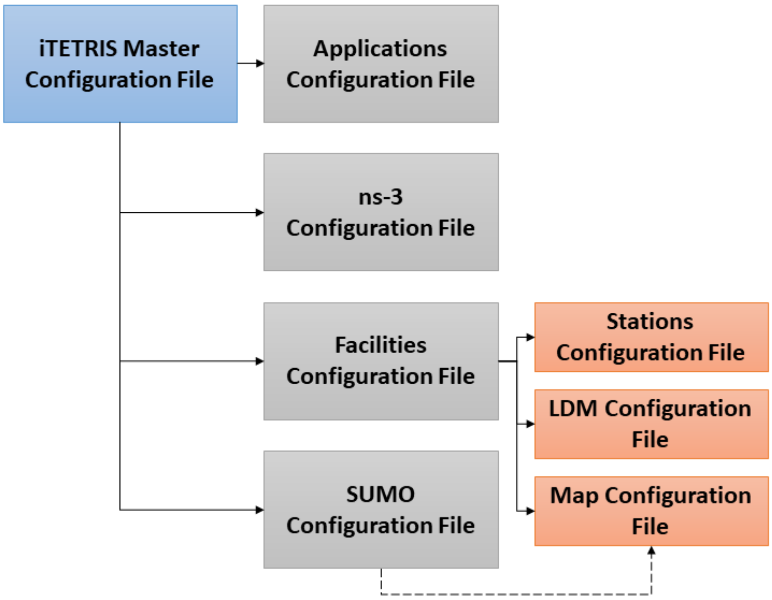

Figure 65: The iTETRIS configuration file hierarchy.

With the purpose of facilitating the fast and easy creation of an iTETRIS Application, the basic yet complete *exampleApp* application is included in the repository. This app is based on the *baseApp* module and can be modified to create new applications.

This *exampleApp* contains the aforementioned necessary configuration files. Please note that all the files and paths mentioned below are located inside the *exampleApp* directory in *TransAIDScenarios*. Under the following paths you will find the config files for a basic TM scenario:

- iTETRIS Master config file: ***config/itetris_cfg_template_tm.xml***
- Applications config file: ***config/ns3/application-config-file-tm.xml***
- ns-3 config file: ***config/ns3/configTechnologies-ics.xml***
- Facilities config file: ***config/ns3/facilities-config-file-tm.xml***
    - Stations config file: ***config/stations-config-file-tm.xml***
    - LDM config file: ***config/LDMrules-config-file.xml***
    - Map config file: ***config/sumo/example.net.xml***
- SUMO config file: ***config/sumo/sumo.cfg***

Example files for a manual scenario are also included (having *manual* instead of *tm* in the filename).

Before making use of the provided *exampleApp*, make sure to have the iTETRIS platform installed and all required environment variables set. To create a basic iTETRIS application, the following steps should be performed:

1. Create a copy of the *exampleApp* directory or simply overwrite it.
2. Modify the above listed files and all those mentioned within them (e.g., the network file, referenced in the SUMO config file) to match the wanted scenario and behaviour.
3. Modify the desired parameters in the ***settings/batchRunner.json*** and ***config/settings/runner-tm.json*** files.
4. Compile / run the application via the command line (using *batchRunner.py*) or using the included GUI tool (*gui.py*). This second approach allows you to change between settings and modify the scenario quickly.

The ***settings/batchRunner.json*** file holds the most important parameters and is the first one called when running the *batchRunner.py* script or when enabling the Json-checkbox in the functionalities section in the GUI tool. It holds the scenario settings such as the vehicle types to be used, seed, level of service (LOS), and traffic mix.

Multiple scenario cases, varying vehicle types, traffic demand levels, network files used, schemes, and even templates can be defined in this JSON file. All these scenario settings will be available to select in the GUI tool (see Figure 66), so that multiple scenarios can be created and run, mixing different combinations of these parameters.

Additional TransAID-relevant parameters (related to RSU, MRM, and ToC) are available to be modified in the ***config/settings/runner-tm.json*** file. More info about the flags and properties present in this file can be found in the ***help/[JsonRunner]-ParametersDefinition.txt*** example file.

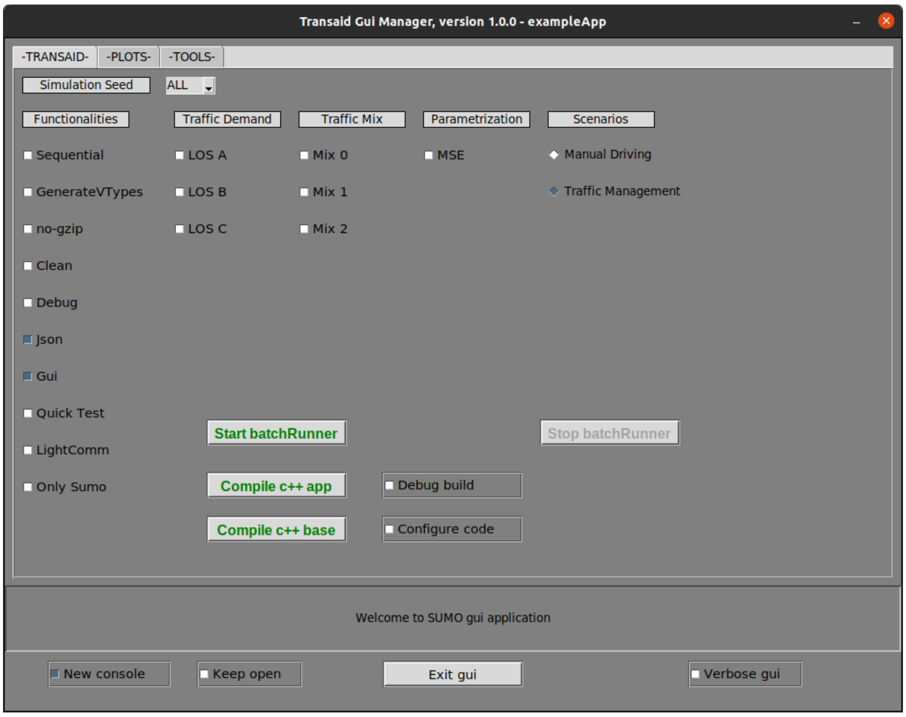

Figure 66: Screenshot of the GUI tool (requires 'tkinter' Python package).

After having modified the *exampleApp* files and its parameters to match the desired new scenario, it is ready to be run. The easiest way is to execute the GUI tool by simply calling *"python gui.py"* in the *exampleApp* base directory. This will open the GUI tool window with three main tabs: TRANSAID, PLOTS, and TOOLS. We will focus on the TRANSAID tab, however, in the other tabs there are many interesting features such as plotting options, enabling the option to show the results folder after the simulation, and even the ability to change the network or open *netedit*.

In the functionalities section, the "Json" option should be checked to enable the use of the previously adjusted JSON specific arguments. Other options that we recommend activating are "Gui" and "Keep open". When hovering over the options, a tooltip describing the element may appear.

Finally, after activating all the desired options in the GUI tool, it is possible to start the simulation by clicking on the "Start batchRunner" button or create the iTETRIS application by selecting "Compile C++ app". Running the simulation opens a new terminal window and can open *sumo-gui* (if selected). If *sumo-gui* opens, it is necessary to click on *Run* (the green play button) in the *sumo-gui* instance to start the simulation. If the "gui" checkbox was not selected in the GUI tool, the simulation will start automatically in the newly opened terminal window.

The resulting files for each simulation will be available inside the *Results* directory, in dedicated folders (and subfolders) for each parameter set and replication/seed. The names of these folders indicate key simulated parameters that were used in that particular iteration (e.g., TM, LOS C etc.), to distinguish and classify the results. The output files depend on the selected options and can consist of XML config files, SUMO related output files, CSV data files, and plot files.

If the option to create the application was selected, the ***build_app.sh*** script will run (this file may need execute permissions to work) and the build process will start in a separate terminal window. Upon completion, the resulting application build will be available inside the ***transaid/iTETRIS-Applications/exampleApp*** directory.