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D.5.3

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Abbreviations and Acronyms

Acronym	Definition
AAE	Autopistas Abertis Espana
ACC	Acceleration Controller
ADAS	Advanced Driver Assistance System
ASF	ASFINAG
ATE	AustriaTech
AV	Automated Vehicles
CACC	Cooperative ACC
CAM	Cooperative Awareness Message
CCAD	Connected and Cooperative Automated Driving
CCV	Connected Conventional Vehicles
CT	Conventional Trailers
CV	Conventional Vehicles
DENM	Decentralized Environmental Notification Message
DLA	Dynamic (Dedicated) Lane Assignment
DoA	Description of Action
FCD	Floating Car Data
HMI	Human Machine Interface
IMC	INFRAMIX Management Centre
IMIS	Intelligent Mobile Information System
ITS	Intelligent Transport System
IVIM	In-Vehicle Information Message
I2X	Infrastructure to everything
KPI	Key Performance Indicator
LKA	Lane Keeping Assistance
LCC	Line Change Controller
LOS	Level of Service
LTE	Long Term Evolution
MTFC	Main Traffic Flow Controller
OBU	On Board Unit
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer

RSU	Road Side Unit
RWZ	RoadWorks Zone
SIE	Siemens
TGAP	Time Gap
TMC	Traffic Management Centre
TOR	Take-Over Request
TP	Trajectory Planning
TTC	Time to Collision
VIF	Virtual Vehicle
VMS	Variable Message Sign
VPN	Virtual Private Network
VSL	Variable Speed Limit
VuT	Vehicle under Test
V2X	Vehicle to Everything

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Executive Summary

Assessment of the impact of INFRAMIX Transport developments is very important to understand how drivers, passengers and transportation stakeholders' lives will change from their application on the roads. Assessment methods included simulation software incorporating microscopic and sub-microscopic modelling of different scenarios and use-cases, mixed-reality approaches (i.e., hybrid testing) for integrating real-life testing with simulation, as well as real-life motorway testing.

The submicroscopic simulation refers to the complete simulation system of a single autonomous ego-vehicle with full authority over vehicle dynamics, control actuators, surround awareness as captured from the simulated sensors and autonomous ADAS functions. In the Hybrid Testing framework, the vehicle dynamics is not simulated but measured, and also the ADAS functions are implemented directly on the vehicle.

The speed recommendation for connected and automated vehicles on the road has positive impact on safety, while lane change policies typically lead to traffic flow inefficiency and generate risky traffic situations (in terms of reduced TTC).

Extensive experiments were carried out using microscopic traffic simulations to obtain a dee per understanding of the conduct of mixed traffic on highways and how mixed traffic can be enhanced using novel control techniques. Using different traffic controllers with more and more connected vehicles on the road offers multiple opportunities to increase the traffic efficiency. Whereas conventional vehicles can only be handled conventionally with advice, e.g. by introducing and monitoring variable message signs, connected vehicles can receive unique advice through ITS-G5 or cellular communication technologies (e.g. LTE or 4G/5G).

The use of the traffic controllers established leads to improved traffic performance. The efficiency could be increased by up to 50 percent compared to an uncontrolled case by using smart time-gap adaptation controllers in traffic management. To avoid expensive investments in infrastructure to deploy VMS at close intervals, solutions were examined that would require fewer VMS and no VMS at all, while relying on communicated traffic advice. In such cases, with a penetration rate of communication capable vehicles (connected and automated ones) of 15-20 per cent or more, improved traffic efficiency values could be achieved. Aside from the performance gains achieved by the controllers, traffic safety shows a minor but acceptable deterioration, since a traffic system with less congestion and higher speeds is naturally accompanied by smaller TTC values.

In Chapter 2 Evaluation high level methodology for traffic efficiency and safety is presented. In Chapter 3 evaluation set up for microscopic and submicroscopic simulations is described.

In Chapters 4, 5 and 6 the Evaluation Setup in Austrian, Spanish sites and hybrid testing respectively is defined. In Chapter 7 the Evaluation results on traffic efficiency and safety are presented. Finally in Chapter 8, an approach to new safety criteria based on simulation results is defined.

1. Introduction

1.1 Purpose of Document

The purpose of this task is to carry out the technological evaluation of INFRAMIX technologie s (including new models of traffic flow, traffic prediction algorithms, traffic control measures) and to evaluate the effectiveness of the proposed infrastructure interventions for mixed tr affic scenarios and different penetration rates for automated and connected vehicles. The analysis will focus on the three scenarios under review, using the methods and indicators described in D5.1. Safety performance and traffic flow efficiency are the main areas for impact to be addressed.

Dedicated simulation scenarios were setup to perform extensive simulation tests using the overall simulation environment developed in WP2. These scenarios included detailed vehicle models, smart vehicle behavior modelling, V2X communication models for connected vehicles, etc.

The indicators that were calculated were based on measurements relevant to the time gaps between vehicles, number of incidents, characteristics of the speed profile, traffic density, traffic demand, travel time etc. Analysis of the data deriving from cases with INFRAMIX improvements and comparison with the base line scenario enabled INFRAMIX to determine the effects on the safety and traffic efficiency indicators selected, an important target of the project.

Concerning safety, the ultimate goal is to identify potential hazards in mixed traffic situations and lay the foundation for the timely implementation of the automation-appropriate and therefore safe infrastructure network.

2. Evaluation Methodology for Traffic Efficiency and Safety

The hybrid road infrastructure is a relatively new research area, which might require new methods of evaluation. The starting point for developing the assessment system used in the project is the FESTA V-process approach, as envisaged in the INFRAMIX DoA.

FESTA (Field opErational teSt supportT Action, 2007-2008) was a project set up to provide detailed guidelines on the assessment and deployment of driver support systems and functions using the technique of field operational testing (FOT). The goal of the FESTA project was to provide a standardized framework to ensure proper evaluation of the systems.

The FESTA Handbook version 7 [1] was used as a starting point to build INFRAMIX's evaluation methodology. This is the version updated in 2018 by the Coordination and Support Action of the CARTRE (Coordination of Automated Road Transport Deployment for Europe), on how FESTA can be used in automated vehicle testing and evaluation projects. INFRAMIX's methodology further adapts FESTA so that the so-called "hybrid" infrastructure can be evaluated in terms of traffic safety and traffic efficiency. See Chapter 2.1 in D5.1.

INFRAMIX retains the key steps of FESTA in carrying out an assessment analysis and adapts the FESTA measures to the goals of the project and the program under review in INFRAMIX.

The resulting approach to INFRAMIX evaluation is shown in Figure 1

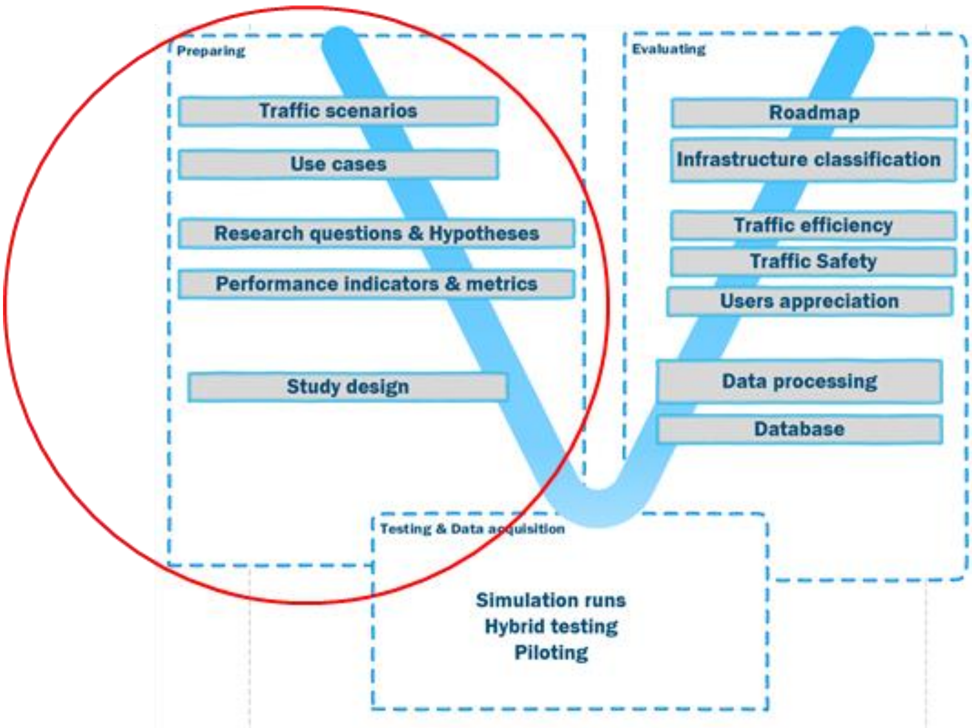


Figure 1. INFRAMIX evaluation approach(inside the red circle the preparation stage is shown)

Microscopic, submicroscopic simulations and hybrid testing were used as important evaluation tools. Measurements of flow, speed and density by class of vehicles (e.g. car; truck; connected or not) by section-lane and by measurement time stage permitted any form of necessary aggregation. Then, most of the indices used for traffic impact assessment of each of the scenarios (e.g. total travel time, total travelled distance, total delay) were measured.

Measurements of flow speed and occupancy per vehicle class (e.g. car; truck; connected or not) per section-lane and per measurement time stage allowed for any sort of aggregation needed and for estimating most of the performance indexes used for simulation evaluation.

However, the extremely low penetration of connected vehicles for an extremely short period of time (i.e. a short slice of time within the peak period) did not allow any use case to be assessed requiring control actions in real-life motorway traffic conditions.

3. Evaluation Setup in Simulation

According to the simulation approach in INFRAMIX, the most important aspects of the real-world test sites are modelled according to the evaluation focus on the individual simulation methods. Please note that each setup is realized by the INFRAMIX co-simulation framework of VSimRTI and ICOS as developed in WP2.

The Austrian test side was selected, with – yet, not limited to – the main focus on safety evaluations. The selection goes well along with synergies of hybrid testing, which is also performed in Austria. Please note that the submicroscopic simulation setup also contains a microscopic component for background traffic. The main difference to the microscopic setup is the more detailed and realistic modelling of one specific Ego vehicle, yet with a limited extent of the experiment playground (highway stretch of 5 km) and a limited experiment time (in the order of 1 minute) as explained later on.

Accordingly, the Spanish site is the basis of the evaluations for traffic efficiency, where microscopic models are prevailing. This site is reflected in a long stretch of 30km and simulation/evaluation time of several hours (3h). In contrast to the submicroscopic setup where measurements mainly regard to the Ego, the evaluation considers all vehicles and the holistic traffic pattern. Also safety can be evaluated in Spanish Site. This will be done in Section 7.1

3.1 Microscopic Simulation – Spanish Site

The microscopic simulations are carried out with the INFRAMIX co-simulation framework. All required models for road traffic, communication, applications, user behaviour, and traffic management are coupled using VSimRTI. The following models are included in the simulations:

- **Map**: The geometry of the road on a microscopic basis.
- **Road Traffic**: Vehicle movements on the highway ressembling real traffic patterns.
- **Communication:** Different communication paths including ITS-G5 and cellular communication (LTE, 4G/5G).
- **Road Infrastructure:** Includes variable message signs for speed limits and lane assignments for AVs, various road detectors which are linked to the controllers, as well as road side units communicating with vehicles via ITS-G5 communication.
- **Traffic management and services:** Collect position data from vehicles (CAM) and distribute advices (IVIM).
- **User behaviour**: Reacting on variable message signs and advices via IVI messages.
- **Vehicle applications:** Includes differentiation in driving behaviour of AVs and conventional vehicles. AVs can furthermore react to advices via IVI messages on their own.

Additionally the INFRAMIX controllers, which are mainly the subject for the microscopic evaluations on the Spanish site, are directly integrated with the simulation environment. Figure 2 illustrates the models included in the microscopic simulations. More detailed information about the models can be found in deliverable D2.2 and D2.4.

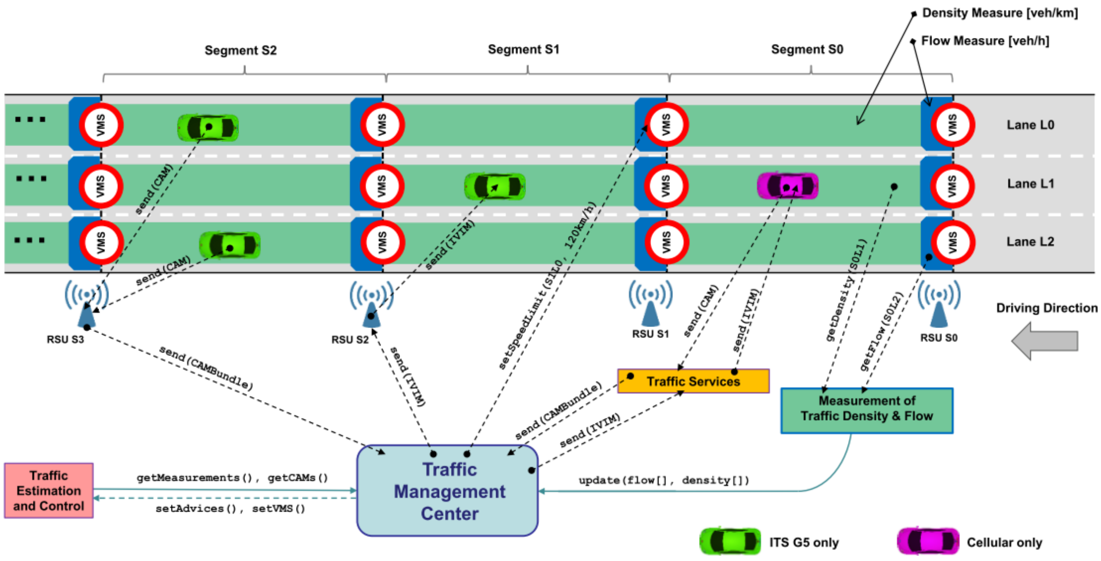


Figure 2. Overview of all models included in the microscopic simulation

Modelling the road traffic for the microscopic simulations was one of the main challenges to solve and has been accomplished in a two step process. On the basis of real toll data provided by AAE a large-scale simulation scenario along the highway AP7 has been created with more than half a million vehicles during a 24h period. This scenario has been calibrated using the the toll data to match the real traffic as close as possible. Since the spanish testsite covers only a little stretch of AP7, the large-scale scenario has been cropped to a 25 km stretch using novel techniques implemented in the co-simulation framework. This final simulation scenario allows to focus the experiments and evaluation on the test-site only and enables simulations faster than real time. The complete process of creating and calibrating the scenario is described in Deliverable D3.3. Both, the large-scale scenario the whole AP7 and the test site section are shown in Figure 3

Figure 3. AP7 modelled in the simulation scenarios (yellow = complete scenario, red = test-site scenario)

The traffic model for the test site has been calibrated to match reality as close as possible, however, no congestion occurs which could be eliminated by applying the INFRAMIX controllers. Therefore, it was decided to add additional synthetic generated traffic demand to one of the highway entries near the end of the test site. This additional traffic is configured with the same mixture of traffic as the main stream.

For the on-ramp on segment 30 (see Figure 4), additional traffic demand is added which constantly grows over time, stays on a contant level for 10 minutes, and is decreased again constantly for a shorter period of time. As a result, the bottleneck is activated as a capacity drop is observed at the merge area of the on-ramp which results in congestion further upstream, as emphasized in the speed contour plots in Figure 5.

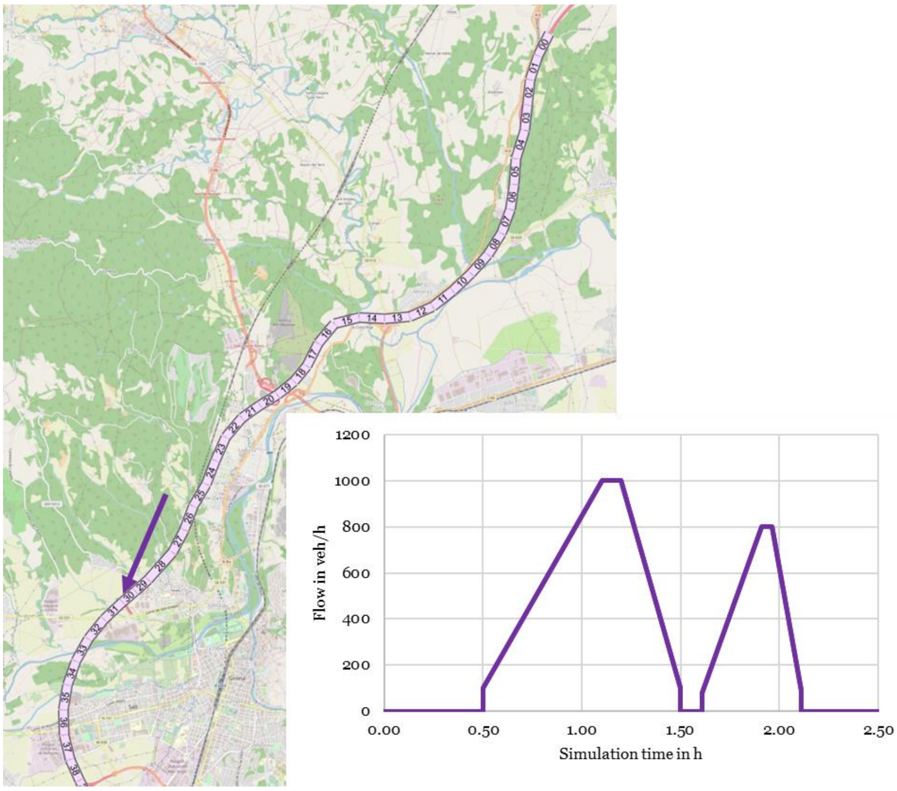


Figure 4. Additional traffic demand injected at segment 30 to reach capacity drop

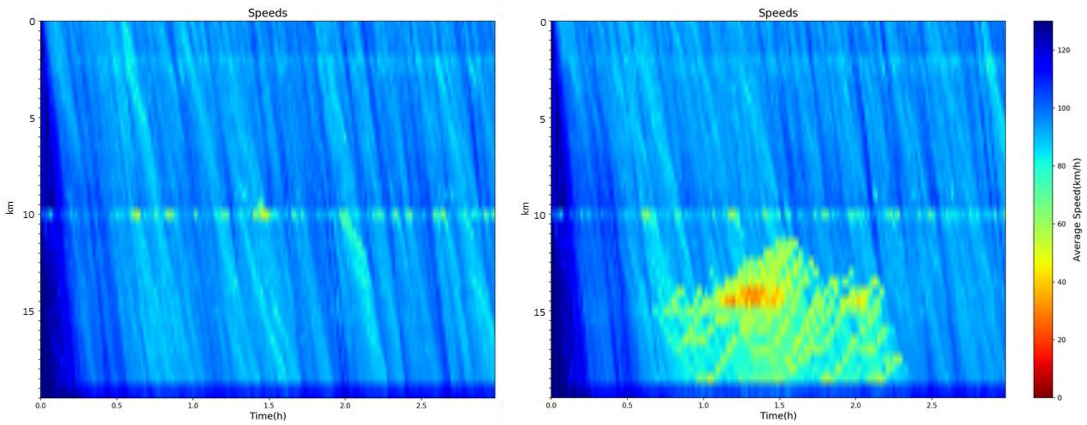


Figure 5. Speed contour plots of situation without (left) and with additiona traffic (right), resulting in a necessary capacity drop and upstream congestion

Simulation Parameters

The simulation scenario can be parametrized in different aspects. In fact, each model provides a various set of parameters. Most of those parameters have been set to fixed values during the calibration process. For a detailed evaluation of the performance of the INFRAMIX controllers, a set of abstract parameters have been introduced which are altered during the simulation series. Those parameters can be categorized in three different groups: Parameters which are relevant for evaluations of the **Bottleneck** scenarios, parameters which are used to evaluate **Dynamic Lane Assignment** scenarios, and ***general parameters*** which have influences on both. The following parameters have been identified:

General parameters:

- **P1 – Traffic Volume**

  Defines the volume of the vehicle traffic on the test site. For AP7, the vehicle traffic derives from real data and resembles a whole day of vehicle traffic. Additionally, synthetic traffic has been added to reach a capacity drop at the on ramp of Girona Oest. The scenario of AP7 Girona used for the evaluations has a pre-configured three-hour window from **8 am until 11 am** which already includes the synthetic traffic. Choosing a different time window within 24h allows to adjust the traffic volume accordingly.

  In addition, the amount of synthetic traffic can be configured. Adjusting this value can be required, as depending on the penetration rate of automated vehicles, the configured traffic flow maxima leads to congestion activation and a related capacity drop sooner or later and therefore to less or more congestion to dissolve.

- **P2 – Communication Link**

  Chooses between the communication link to be applied for the simulation. Communication between vehicles and the TMC is either modelled via the cellular link, or via ITS-G5 including road side units which are located along the road (e.g. on each segment border). It can be switched between:

  - **No communication** would disable any message distribution amongst vehicles and the TMC. Only the VMS could be used to control the traffic.
  - **Cellular Communcation** models communication over the cellular link, e.g. LTE or 4G/5G. Vehicles communicate with the TMC directly, no additional infrastructure is required in the simuation.
  - **ITS-G5 with high RSU coverage** models direct communication via ITS-G5. Vehicles are connected with road side units, which are placed at each segment (every 500m).
  - **ITS-G5 with low RSU coverage** models direct communication via ITS-G5 as well. In this case, road side units are placed with higher distance, e.g. every 5 km on every tenth segment.

- **P3 – TMC Update Interval**

  Vehicle messages (CAMs) are sent to the TMC and are aggregated before making control decisions. This parameter defines in which interval those messages are collected and aggregated and therefore, in which interval control decisions are made. Typical variations could be **15 seconds** or **60 seconds** of update interval.

- **P4 – Penetration Rate**

  Defines how many vehicles are equipped with autonomous driving functions and communication facilities. Both dimensions (**% of AVs and % of CCVs**) can be parametrized individually, whereas AVs always have a communication link enabled and react on advices per default.

  Even though the penetration rate can be freely configured, we propose the following six configurations which take typical market penetrations into account (Figure 6).

  In all following charts and tables, the penetration rate is noted with the scheme "CV-CCV-AV". E.g. the term "94-04-02" means 94% of vehicles are conventional, 4% are connected conventional vehicles, and 2% have automated vehicle functions.

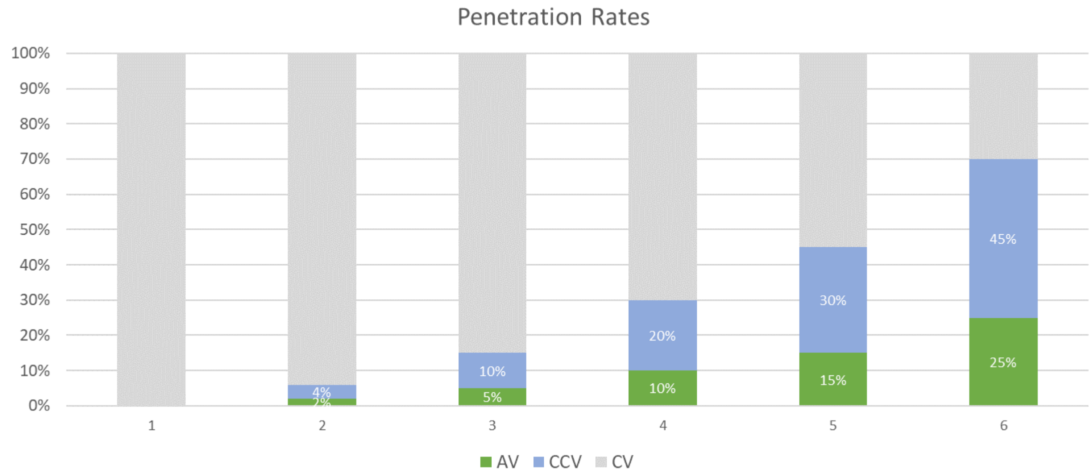


Figure 6. Proposed penetration rate configurations for the evaluation series

Specific Parametrizations for DLA scenarios

- **P5 – AV Lane Position**

  Defines the position of the dynamic AV lane on the test site. AV lanes are either activated on the rightmost, or leftmost lane of the highway.

Specific Parametrizations for Bottlneck scenarios

- **P6 – Segmentation**

  Defines how the segmentation of the highway is supported by the infrastructure (VMS and sensors). In the preconfigured scenario of the test site, the highway is divided in 40 segments which all include detectors and variable speed signs at the entries/exits of each segment. This segmentation could be parametrized by

  - Applying **VMS and detectors for each segment.**

- Applying **VMS and detectors for some segments** only. Variable speed signs exist only after on-ramps and at strategic relevant places along the highway.
- **No infrastructure at all,** all segments are pure virtual in the controller. This implies that communication is required and that vehicles, which receive advices from the controller via IVI messages, can react to them accordingly.

- **P7 – INFRAMIX control algorithm variations**

  Chooses between the different advices the TMC should send to the vehicles and VMS. The advices include speed advices, lane change advices. This is achieved by using and combining the different INFRAMIX controllers:

  - **VSL control** controls the traffic by setting speed limits by using VMS dynamically.
  - **VSL control with V2X** controls the traffic by setting speed limits by using VMS dynamically and sends out speed advices via IVI messages.
  - **Lane Change Control (LCC)** tries to prevent congestion by moving individual vehicles to other lanes by sending out lane change advices via IVI messages.
  - **Gap & Acceleration Control (ACC)** advices autonomous vehicles to reduce or increase their time headway to increase capacity on the highway.
  - **Any combination of the above**

Furthermore the **random seed** of the simulation run can be changed in order to gain meaningfull results. The following parts of the models are affected by the random seed:

- The time of departure of each vehicle.
- The vehicle dynamics (speed limit adaption, distance behaviour when following car).
- The assignment of each individual vehicle to CV, CCV, and AV, according to the given penetration rate.
- The reaction on VMS and received advices.
- The distribution of V2X messages.

Performance Indicators

The following Key Performance Indicators can be gathered from each simulation run:

- **K1 - Average Travel Time**

  Provides the average travel time (in seconds) for each individual or group of vehicles (CV, CCV, AVs) and for all vehicles in total. The travel time for each vehicle is calculated by subtracting the time of departure from the time of arrival.

- **K2 – Total Time Travelled**

Provides the total time traveled during the whole simulation over all vehicles. The Total Time Travelled is calculated by the sum over the number of vehicles in each segment and each time step.

- **K3 – Mean Speed, Density, Flow over Time for each Segment**

  For each segment, various traffic properties are aggregated for fixed intervals (e.g. 300 seconds, independent of application configuration). Based on this data, speed contour plots and fundamental diagrams can be created.

- **K4 – Average Harmonic Speed**

  Measures the harmonic speed of each vehicle and averaged over all vehicles or group of vehicles.

- **K5 – Average Delay Time**

  For each vehicle the travel time compared to the fastest vehicle on the same route is compared and stored (the assumption is that the first vehicles would have a free flow travel). The delay times are again averaged over all vehicles or group of vehicles.

- **K6 – Average Number of Stops**

  Counts the number of stops for each vehicle. A stop is identified if a vehicle's speed exceeds 2 m/s after it went below 1 m/s.

- **K7 – Average Fuel Consumption**

  Measures the average fuel consumption for each individual vehicle (in l/km).

- **K8 – Time-to-Collision Frequencies**

  Time to Collision(TTC) is the remaining time before the rear-end accident if the course and speed of vehicles are maintained. For each vehicle the TTC (in seconds) is calculated in each simulation step and categorized into groups of intervals of 0.1 seconds. For each interval, a total number of occurences is gatherd. This KPI can be used to deduce safety impacts from the use of the INFRAMIX controllers and dedicated lane assignments.

3.2 Submicroscopic Simulation – Austrian Site

Deliverable 5.1 *Plan for evaluation and users' engagement* [5] contains a list of performance indicators of the entire co-simulation platform. That means the sub-microscopic simulation from Virtual Vehicle as well as the microscopic co-simulation VSimRTI from FOK. ViF is investigating sub-microscopic cases which are limited to specific segment (segment 3) of the Austrian site and restricted in simulation time.

These short simulations are repeated 60 times and most of the results are averaged over all 60 repetitions. The following list gives an overview of the performance indicators available in the submicroscopic evaluation:

- Travel time (average and deviation) for different classes of vehicles
- Time gap
- Time spent in a section/segment[1]
- Harmonic speed
- Distance to merge
- Time to Collision (TTC)
- Mean speed (average and deviation) for different classes of vehicles
- Vehicle has merged successfully/not successfully
- Number of stops (average and deviation) for different classes of vehicles

3.2.1 Scenario description – Bottleneck – Onramp

The current result discussion is related to simulations with a focus on bottlenecks on motorways. All simulations were conducted on a specific road stretch of the motorway A2 in Austria. The VuT (Vehicle under Test), an automated vehicle comes from the onramp and tries to merge into the mixed traffic of the main road.

The VuT is simulated with the sub-microscopic framework, while the mixed traffic is modelled in SUMO and simulated in the VSimRTI framework. Both parts are coupled and interact together. (See Deliverable 2.3 *Specification of sub-microscopic modelling for intelligent vehicle behaviour*) [4].

To achieve a steady state of the traffic situation on the main road a so-called pre-simulation of 300 seconds has to be done before the VuT starts on the onramp. The idea of this scenario is the investigation of one automated vehicle during threading on the traffic on the main road in the area of an onramp as well as its own behaviour. Firstly, baseline simulations are conducted. They build up the basis for a comparison with

[1] In evaluation of submicroscopic simulation 'travel time' and 'Time spend in section/segment' are the same.

simulations including infrastructure measures. By means of that comparison, an identification of the frequency of critical situations is possible.

In what follows, the simulation setup for the baseline as well as the measure simulations are explained.

Baseline Simulation

As already mentioned, the VuT drives in this scenario on the onramp. Since there is no additional infrastructure measure present, the vehicles on the main road as well as the VuT drive according the traffic rules. That means with a maximum speed of 130 km/h.

Measure Simulation with Speed Advice

The first measure simulation focuses on the investigation of traffic effects when the maximum allowed speed is reduced from 130km/h to 100 km/h in segment 3. A variable message sign (VMS) indicates that the maximums speed in segment 3 is now limited to 100 km/h. Additionally automated vehicles are informed via IVI message about the new speed limit of 100 km/h.

Measure Simulation with Speed and Lane Change Advice

The second measure simulation includes another measure. Now, automated vehicles get additionally a lane change advice for segment 3. The idea is to improve the merging behaviour on the onramp by forcing automated vehicles to leave the rightmost lane and open gaps for merging vehicles coming from the onramp. The automated vehicles are informed via CITS-message to leave their current lane and change to the left lane.

Road network

The basis of the road network is one part of the Austrian test site on the motorway A2. This motorway section consists of approximately 5 km with three lanes and one onramp. The lane widths range from 3.5 m to 3.75 m. This onramp is at airport Graz (Km183, N47.009° E15.439°) and has a acceleration length of 250 m. Besides the typical character of an onramp, this motorway section is part of *Alp.Lab*, a twenty-kilometer-long test track which is equipped with a huge sensor system used to provide information about the traffic flow.

Inside the microscopic simulation SUMO and the whole framework (VSimRTI coupled with submicroscopic simulation from ViF) this road section is divided in four segments. Since the current analysis focuses mainly on traffic behaviour in the near vicinity of the onramp, which is located in segment 3, all evaluations are related to that segment.

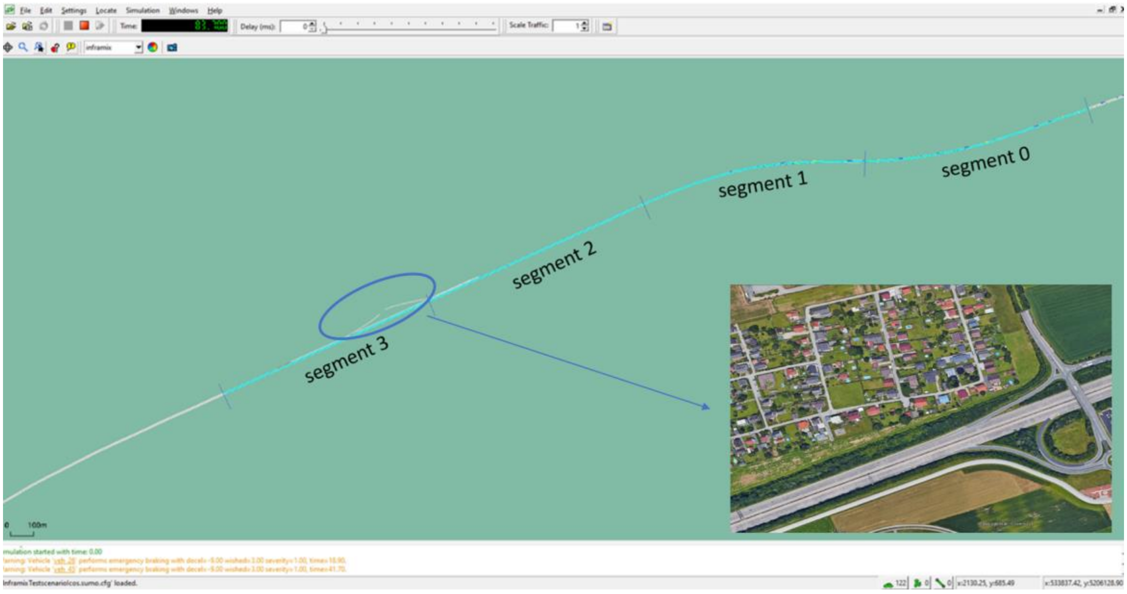


Figure 7. Road network

Traffic Parameterization

The Traffic parameterization is based on measurement data from ASF on this road stretch. The measurement data were used as input data for an optimization of the parameters of the traffic. The used optimization procedure can be found in [6].
The different densities of the traffic are divided into four level of services (LOS). These LOS are an input parameter for the simulation whereby 60 simulations were made for every LOS.

Table 1. Traffic flow configuration based on Asfinag Data

Flow	Flow
-	veh/h
LOS A	1580
LOS B	3065
LOS C	4410
LOS E	5180

From the measurement data also an average distribution of vehicle types was derived. Nowadays, traffic consists only of conventional vehicles so that an assumption of automated vehicles has to be done for the simulation. Therefore, the current ratio of 85.7% conventional vehicles, was divided in 25% automated passenger cars and 75% of conventional passenger vehicles.

Table 2. Percentage of different vehicle types

Vehicle Type	Part of the flow
Conventional vehicles	64.5%
Automated vehicles	21.2%
Motorcycles	2.3%
Trucks	4.7%

Trailers	6.9%

3.2.2 Scenario description – Bottleneck – Main Road

Now, the VuT is driving on the main road. When the VuT approaches segment 3 there is driving mixed traffic along the onramp and try to merge into the main traffic.

Baseline Simulation and Measure Simulations

As in the previous scenario description, the baseline simulation without infrastructure measures built up the basis for comparisons with measure simulations. In this scenario we use the same measures as before. Firstly, a speed advice as infrastructure measure and secondly, a combination of a speed and lane change advice.

Traffic parametrisation

The same traffic specification as before is used. Additionally, 10% of the traffic on the main road is now generated at the onramp.

Table 3. Traffic Flow Demanded

Level of Service	Flow Main Road	Flow Onramp
-	veh/h	veh/h
LOS A	1580	158
LOS B	3065	307
LOS C	4410	441
LOS E	5180	518

3.2.3 Scenario description – Roadworks zone

In the roadworks scenario the focus is on the investigation of the impact caused by infrastructure measures on one specific automated vehicle. In this specific scenario the measure is presented by a C-ITS-message, which informs the VuT about an upcoming roadworks zone.

For the current scenario the same road stretch with the same division of segments as in the bottleneck scenario is used (see Section 3.2.1 for the scenario description). In the current analysis however, a roadwork zone is defined in Segment-3. The rightmost lane in Segment-3 is blocked and is not available for the traffic to enter, throughout the segment. Also the onramp in segment 3 was modelled as closed. Thus, only 2 lanes remain for the whole traffic in Segment-3.

In the current study, the VuT is simulated again with the sub-microscopic co-simulation framework, while the mixed traffic flow is modelled using SUMO and simulated in the VSimRTI framework. We note that both SUMO an VSimRTI are coupled through co-simulatoin and interact together. To obtain sufficient statistical samples, each simulation setup was simulated 60 times with varying random seeds.

In each simulation the VuT starts at the beginning of the simulated road stretch. The bottleneck in this scenario is the intersection point between Segment-2 and Segment-3. In Segment-2 there are three full lanes available, which are later reduced down to two lanes in Segment-3.

Roadwork zone simulations were conducted with SUMO Version 1.5, not in SUMO 1.4 as with the bottleneck scenarios. Also the VSimRTI Version was upgraded to 'vsimrti-inframix-19.0.inframix.20200313' during the Roadworks zone analyzes.

Baseline and Measure Simulation

In general DENM messages are event based messages and can be used to inform traffic participants about upcoming events like roadwork zones or accidents. This message includes among other things information about the relevance zone of the event, utilization of lanes as well as speed limits. Due to the increasing number of messages, the processing of these message contents in a car is getting more complex and could not be managed in a detailed way. To demonstrate at least one roadworkzone scenario we prepared a straightforward solution that can later be extended further for more complex use case analyses and studies.

In the baseline simulation the VuT has to merge into the remaining lanes whereby the vehicle detects the upcoming roadworkzone with its own sensors.

In the measure scenario the VuT is supported by the infrastructure with a DENM message, which informs the VuT about the upcoming roadworkszone 400 m before it starts. In this scenario only the VuT is affected by this ITS-message. For both scenarios, the speed limit along the roadwork zone is reduced to 100km/h and is indicated by the VMS for the conventional traffic and as IVI message for automated vehicles.

In the following sections the results of the roadworkzone scenario analysis will be presented, first describing the traffic parametrization and then the results for the *mean speed*, *travel time*, *minimum time gap* and *TTC* as traffic specific KPIs. These specific KPIs were chosen to understand the effect of the infrastructure messages on the traffic performance parameters through a comparison between the baseline and the measure simulations. Please note that the *number of merges* and the *distance to merge* metrics are ego vehicle specific parameters, which describe the effect of the measure signal on the VuT alone.

Traffic parametrisation

In this analysis the same traffic flow parameters as in the scenario Bottleneck - Onramp is used. See chapter 3.2.1 for the details. The levels of service (LOS) were calculated for the motorway with 3 lanes without the roadworks zone (i.e., in the LOS calculation Segment-3 with the roadworks zone is not taken into account). Speicifcally, these LOS values represent the traffic densities in the Segment-0 and Segment-1, long before the roadworks zone, in which the effects of the roadworks zone are not visible.

4. Evaluation Setup in real-world Austrian Site

The test site in Graz, Austria, was used to demonstrate the three traffic scenarios:

- SC1: Dedicated lane assignment,
- SC2: Roadworks, and
- SC3: Bottlenecks,

in real world operational conditions.

This was done by real world test and demonstration drives on the test track,the respective Deliverable focussing on these test is D.4.2.

Further two traffic control strategies have been implemented, namely the mainstream traffic flow controller via VSL and the ACC parameters adaptation controller. The respective Deliverable focussing on these test is D.3.4.

4.1 Test Days on the Austrian Test side:

4.1.1 ITS-G5 Communication Tests (May 2019)

Table 4. Messages for the communication test

C-ITS Message	C-ITS Message Type	C-ITS Day1	C-ITS Day2	Scenarios
Vehicle type and lane specific speed recommendation for automated vehicles	IVIM		X	
Vehicle type and lane specific speed limit for automated vehicles	IVIM		X	
Lane recommendation: Dedicated lane assignment SAE level clearance for automated vehicles, level of automation	IVIM		X	
Short term road works warning	DENM	X		
Lane specific time gap advice	IVIM		X	
Long term road works warning/ road works layer lane recommendation: Specification of new lane design in long-term road works zone	MAPEM / IVIM	(X)	X	
Basic hazardous location warnings	DENM	X		
Awareness message about existence of other vehicles/	CPM		X	

Collective perception of objects on the road				
Traffic condition (heavy rain)	DENM	X		
GNSS correction data	RTCM		X	

As a pretest for the October Test (see next section), the INFRAMIX message set and some additional Day 1 / Day 2 messages were tested on May 9, 2019 on the Austrian test track. The partners involved were SIE, ATE, VIF and ASF. The base was located at the ASFINAG highway maintenance centre in Graz Raaba (ABM Raaba). The test comprised of the message sets as specified in Table 4**,** which includes all messages which were identified as relevant for the INFRAMIX project. These tests were the first ones in which C-ITS Day 2 messages were sent out and received successfully in Europe. More details about the tests and the results can be found in D4.2.

4.1.2 October Tests

The October tests took place from Oct 07, 2019 to Oct 11, 2019 again with basecamp at the ASFINAG highway maintenance centre Raaba (ABM Raaba). The aim of these tests was to mimic the INFRAMIX scenarios and possible related message sets "Mockups" (and the corresponding control strategies). This is laid out in detail in the following sections. The messages on which those "mockups" were built on had all already been pretested in the test in May, so that these tests could focus on the mockups with stable message sets.

The test week was accompanied by attractive side events as the Stakeholder Workshop (see Deliverable 6.10 and 5.2) the ACstyria Business lounge and the INFRAMIX face-to-face meeting. All those side events made it possible to present the INFRAMIX approach to a considerable audience of stakeholders. Also, in all of those events, it was possible to join a test drive of the C-Roads vehicle of ATE. Participants who made use of this offer were asked to fill in questionnaires for the user appreciation; approximately 30 (both in the ACstyria Business lounge and the INFRAMIX Workshop) did so.

In the following an overview of the demonstrated scenarios is given. For further details about the tests the reader is referred to D 4.2. which contains a detailed summary.

4.1.2.1 Scenario 1: Dedicated Lane Assignment (East loop)

Scenario 1 was sent out on the East loop of the test track in order to have longer segments without on or off ramps. As for all scenarios, a different message set was designed for each driving direction.

SC1 UC2 was covered in Driving Direction 2 where there is the adverse weather condition warning within the relevance zone of the DLA.

Figure 8. Dedicated lane assignment (DLA)

Driving direction East (DD2)

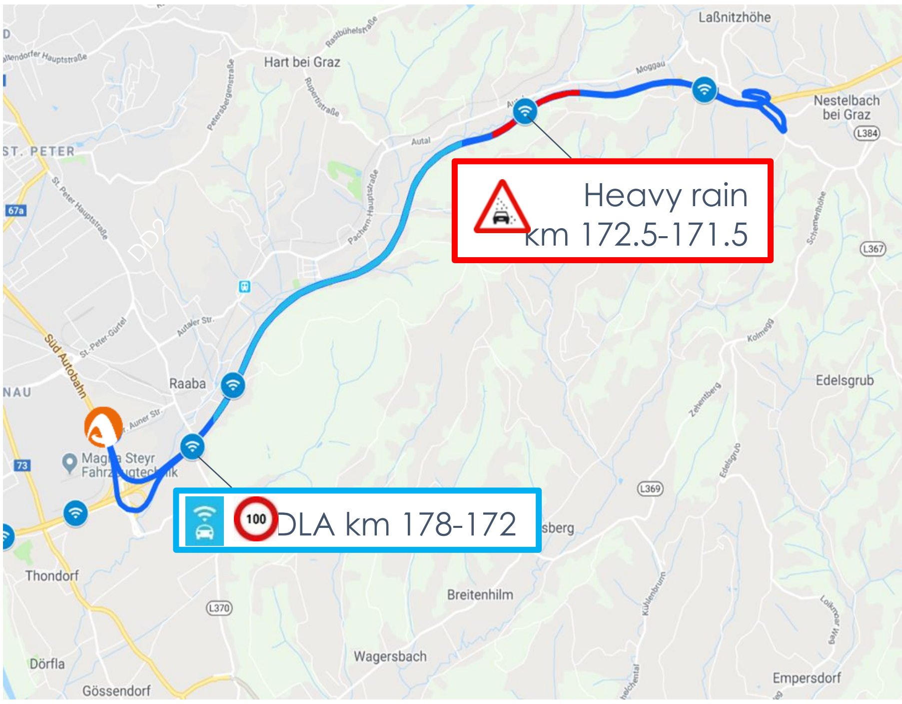


Figure 9. SC1 DD2 East loop

Driving direction West (DD1)

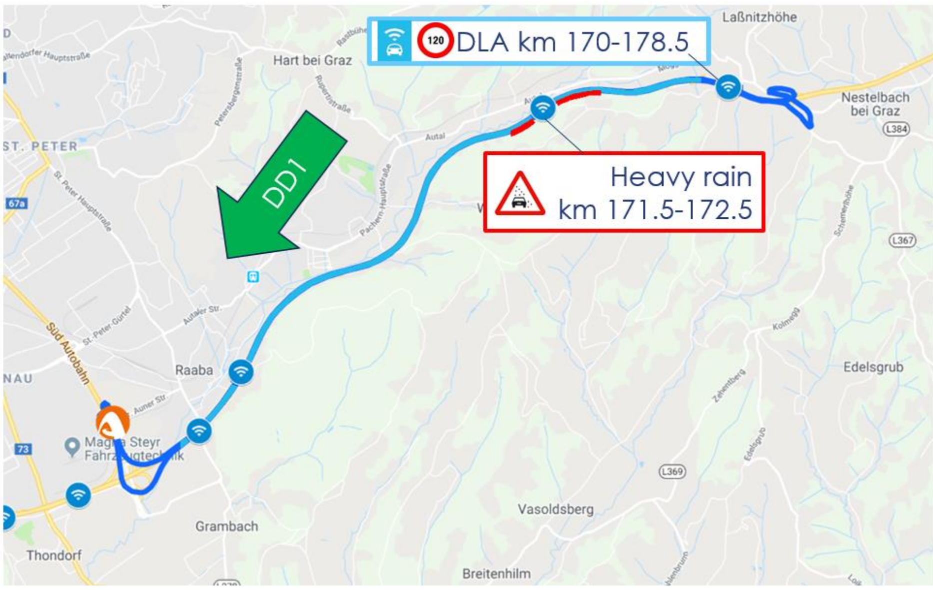


Figure 10. SC1 DD1 East loop

4.1.2.2 Scenario 3: Bottleneck (West loop)

We will first discuss the setup of Scenario 3 before laying out Scenario 2. The reason will become clear in the following. SC3 was sent out on the West loop, the corresponding bottlenecks are the on-ramps around km 183.5 “Flughafen Graz”. Note that this is the same ramp that was used for the sub-microscopic simulations. The different possible control strategies were addressed by sending out a distance gap advice in one driving direction, but a lane change advice in the other one.

Figure 11. Bottleneck

Driving direction West (DD1)

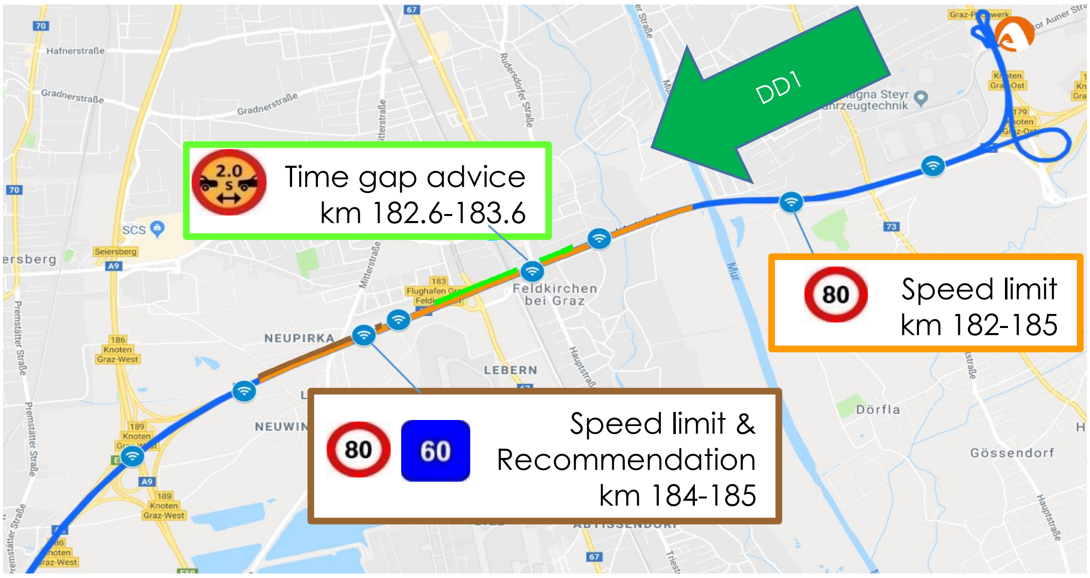


Figure 12. SC3 DD1 West loop

Driving direction East (DD2)

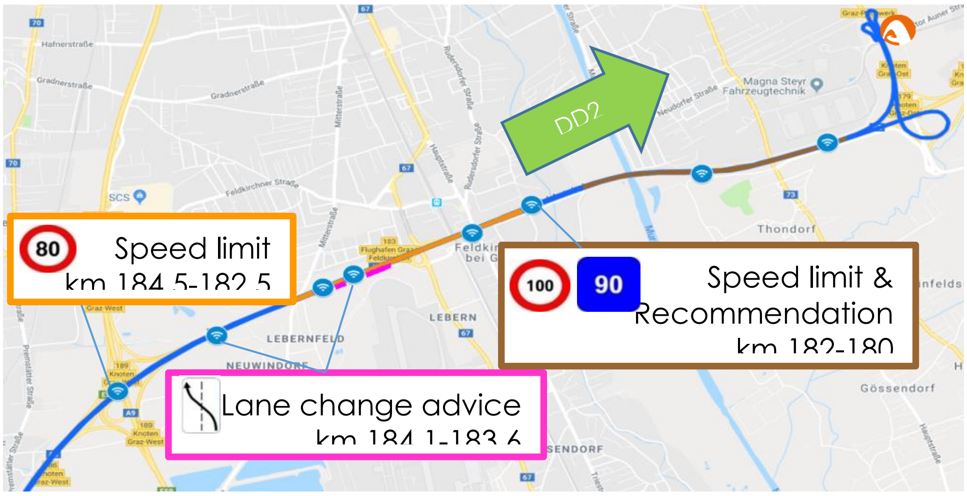


Figure 13. SC3 DD2 West loop

4.1.2.3 Scenario 2: Roadworks (West loop)

Since control strategies for the roadworks zone (especially with lane drop) were identified to be very similar as for the bottlenecks, the test setup for SC2 was chosen in a very similar way as for SC3. When comparing Figure 12 to Figure 15 or similar Figure 13 to Figure 16 one can see that they mainly differ in the additional roadworks warning which was added for each driving direction. For indicating the roadworks zone, an IMIS trailer was used.

Figure 14. Roadworks

Driving direction West (DD1)

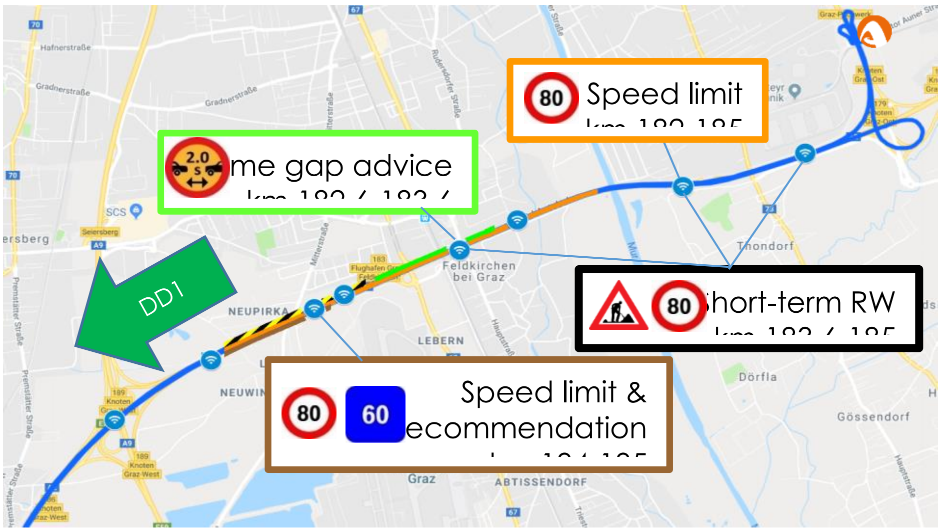


Figure 15. SC2 DD1 West loop

Driving direction East (DD2)

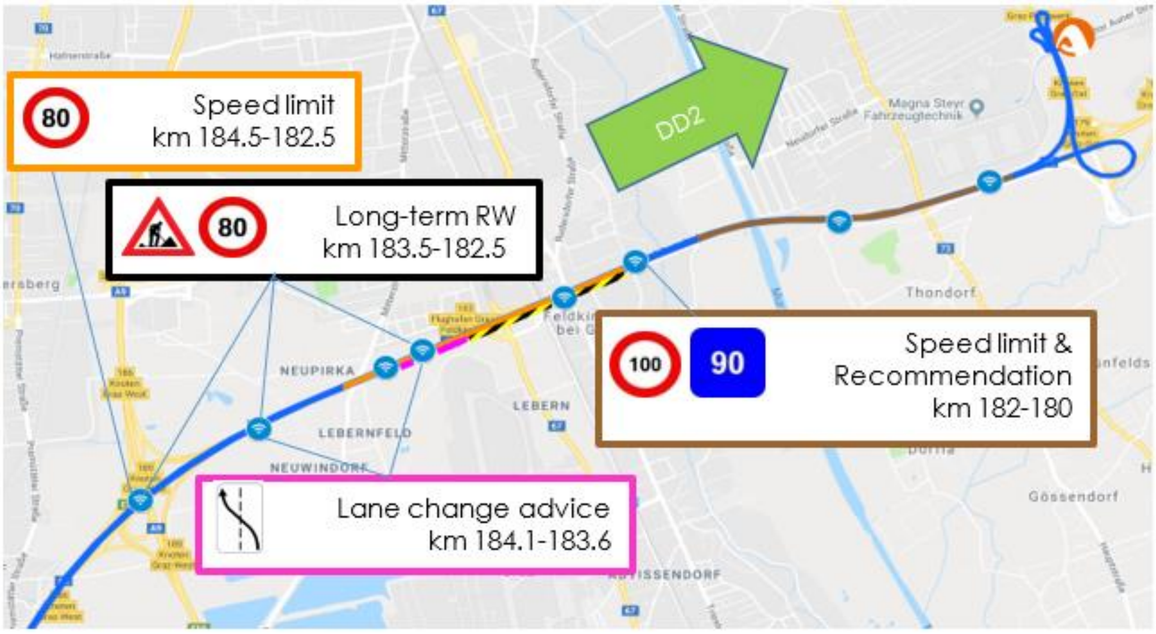


Figure 16. SC2 DD2 West loop

4.2 Traffic Control Strategies:

A part of the Austrian test site (south-bound) was used for testing the implementation of the traffic management strategies. Table 5 presents the segmentation used for this purpose as well as the location of the corresponding detectors. Deliverable 3.4 includes the input files used by the API and the controllers while running the system as well as more detailed description of the approach.

For the test ASF assured the aggregation in the required format and a push service to the SIE server on which the respective control strategies were implemented. This required data conversion into the .json format required by the services and a strategy to aggregate the sensor data in one-minute intervals. Further the VPN connection and the push service to the SIE server had to be implemented and tested in order to assure the data flow and quality required for testing the control strategies.

Table 5. Segmentation and detector groups used for the Austrian test site

Segment id	start (km)	finish (km)	length (km)	detector id	detector location (km)	detector lanes
segment01	183.3	183.9	0.6	detector01	183.9	3
segment02	183.9	184.5	0.6	detector02	184.5	3
segment03	184.5	185.1	0.6	detector03	185.1	2
segment04	185.1	186.6	1.5	detector04	186.6	3

Based on the information presented in Table 5, the layout of the Austrian test site used has been prepared and is presented in Figure 17. This section includes results that have been produced using data from the 24th of October 2019. This is, in fact, a typical day for the specific area of the test site and, as discussed in D3.4, based on the data received from the detectors, no congestion phenomena appear. As, based on TomTom historical data, there is a higher probability for congestion on Fridays, similar tests were performed on a couple of Fridays without any congestion present at the bottleneck area (segment04). On the other hand, congestion was present in some cases at segment03 and segment02 due to a spillback from the off-ramp located in the area. It has to be noted at this point that congestion phenomena that appear on motorways and are due to external factors cannot be treated using local control actions and may require other types of control, e.g. demand management, dynamic traffic assignment.

A detailed description of the method and results can be found in D3.4.

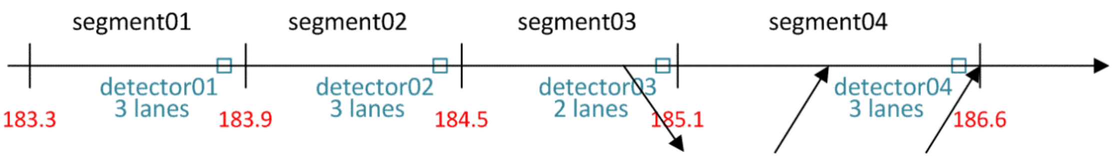


Figure 17. Layout of the Austrian test site used

5. Evaluation Setup in real-world Spanish Site

The Spanish test site is operated by Autopistas and utilized to test and validate infrastructure elements and upgraded ITS services designed for assisting automated vehicles, and for providing management capacities to control mixed traffic in different scenarios. It is located along the Mediterranean Corridor, between Barcelona and the Spanish/French border. It is 20km long with four main intersections and a 180m tunnel. The highway with four 3,5m wide, and a median of 5m. Its internal hard shoulders measure 1m and external ones 2,5 m. The Average Daily Traffic (ADT) on the test site is estimated at 30.000 vehicles per day, and the default speed limit is 120km/h.

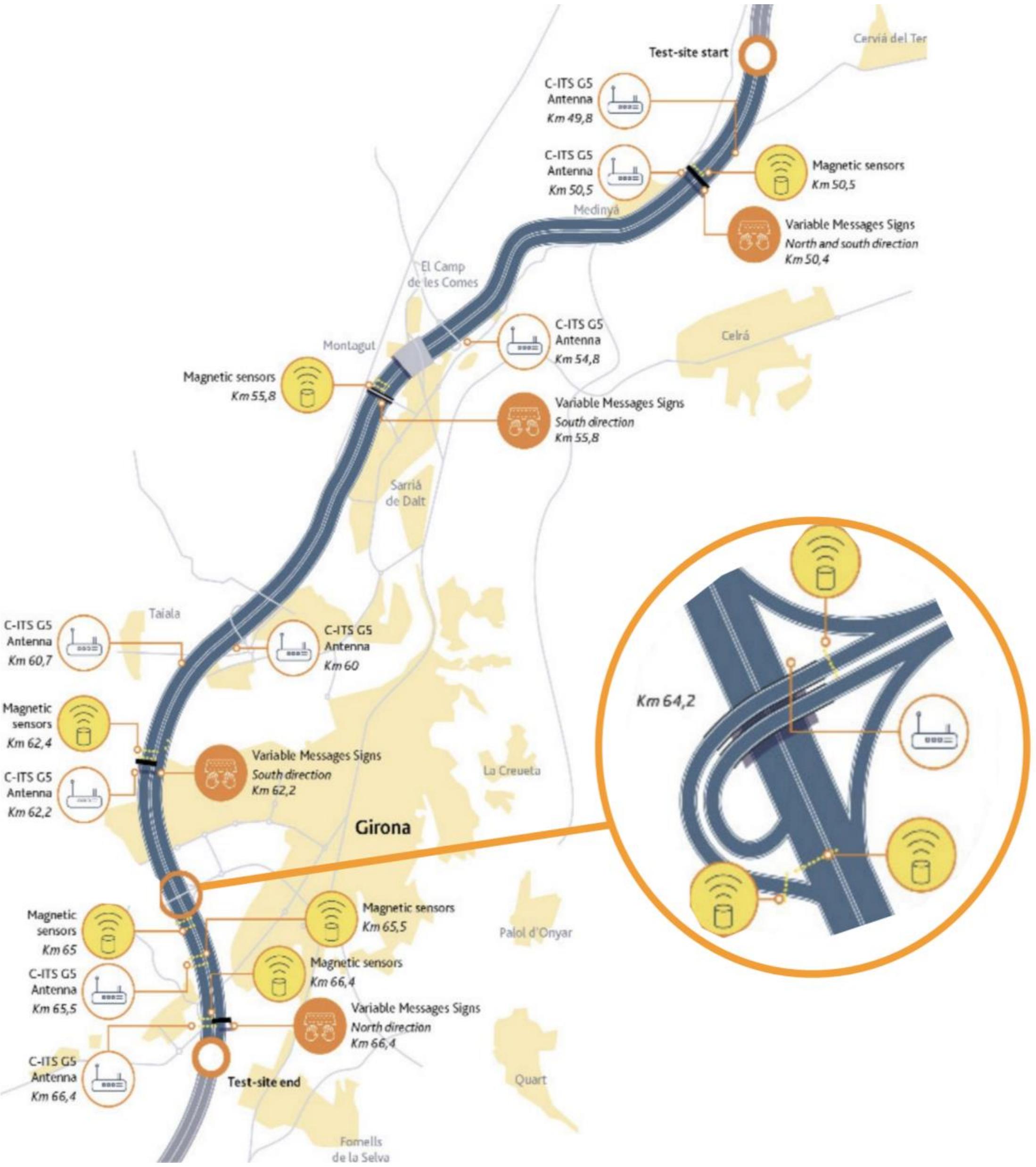


Figure 18. Map of the Spanish test site

The test site is equipped with traffic monitoring and communication infrastructure to enable testing and evaluation of C-ITS solutions and applications for connected and automated vehicles. The currently ITS equipments includes different types of VMSs, CCTV cameras, Bluetooth antennas, magnetic sensors for traffic detection, and a weather station. Communication is supported by both ITS-G5 short range systems and cellular communication, in addition to a dedicated fiber-optic ring network with 1GB bandwidth capacity, connecting ITS equipments to the traffic management center.

In addition, for the INFRAMIX demonstrations, five pictograms were painted every 100 meters on the floor of the fourth lane of the test site to signal the start of a dedicated lane for autonomous vehicles. Also, three vertical signals were installed to indicate the proximity of the dedicated lane, and a fourth one to indicate its end.

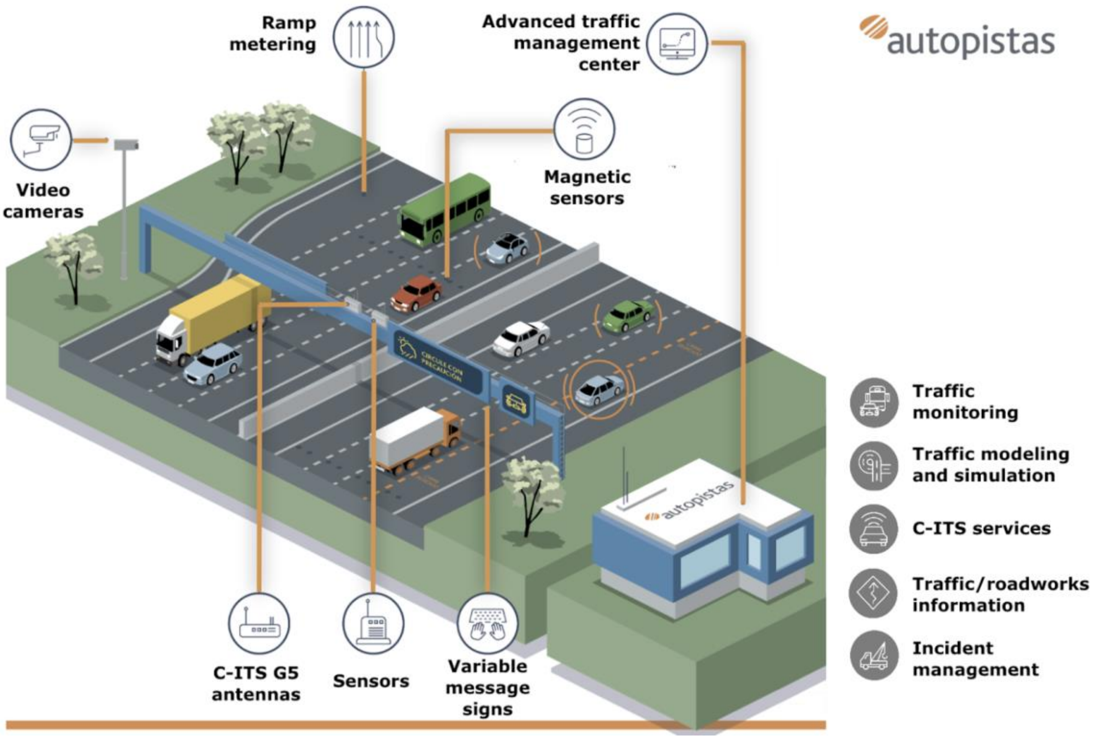


Figure 19. Test site schematic design and functionalities supported

5.1 Sensing, communication, and data management systems

The test site implements the INFRAMIX hybrid road infrastructure concept as defined and described in D2.1 “Requirements catalogue from the status quo analysis”. In order to implement this concept, the required sensing and communication systems were installed, upgraded, or/and made available on the Spanish test site. These include the following highway sensors and systems:

- **4 Variable Message Signs**, the first is located at 1.5km from the beginning of the test site, and the fourth a few hundred meters before its end. The remaining two VMS are located outside the tunnel and near one of the main intersections.
- **3 ITS-G5 Road Side Units** (RSUs) acquired and connected to the IMC, to send and receive ITS-G5 messages to an ITS-G5 On Board Units (OBUs) installed in vehicles.
- **60 wireless magnetometer sensors** that count the number and speed of vehicles per lane, and are able to discern different types of vehicles and the time-gap between them, as they pass on the highway.

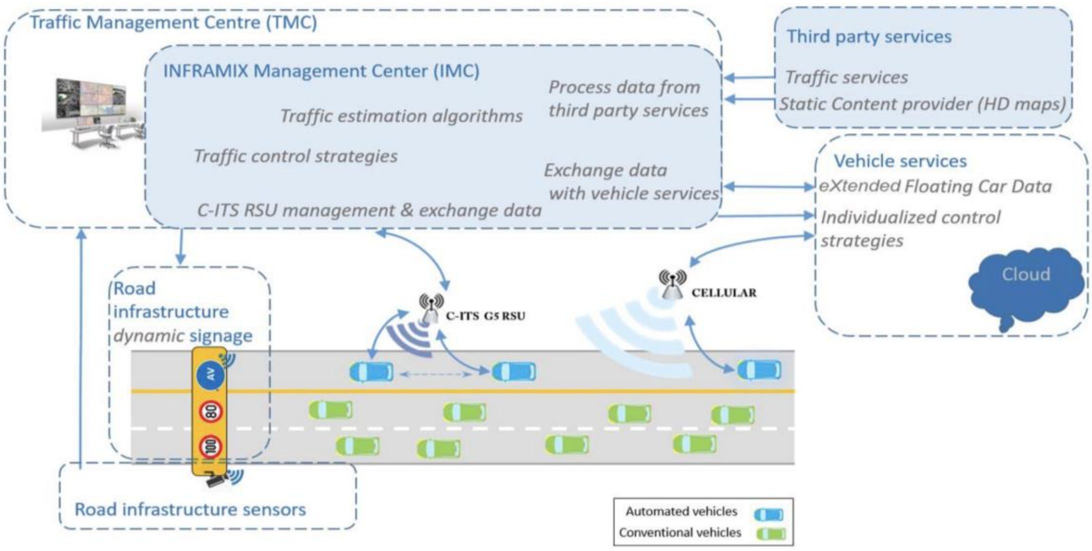


Figure 20. High-level representation of the INFRAMIX hybrid road infrastructure concept

In addition to the hardware infrastructure installed and made ready on the test site, the following digital infrastructure was integrated to conduct the tests:

- **Autopista's Traffic Management Center** (TMC) receives traffic data from sensors in real-time and controls the content of the VMS dynamically. This is simulated by Autopista's Hub system, which integrates data from different sources and API in real-time and is able to control the VMS content.
- **The INFRAMIX Management Center** (IMC) acts like an extension of the TMC, implemented as a separate module with real-time bidirectional communication with the TMC. It estimates and analyzes traffic flows based on traffic sensor data and other sources, implements the traffic control strategies related to a specific use case and its settings, manages and exchanges data with the installed ITS-G5 RSUs and the Cellular Experiments Server, and integrates data sources from third-party services.
- **The Cellular Experiments Server** consists of an experimental link that receives messages from IMC, and relays them to an experiment mobile App installed in the vehicle, via bidirectional communication. In addition, it interfaces with the backend systems of vehicle services (in this case the BMW vehicle services Backend).

- **The BMW vehicle services Backend**, which communicates with IMC via the CES, and provides data collected from BMW vehicles and relays messages to the vehicles in real-time.

5.2 Test vehicles and convoy configuration

A total of five vehicles were made available for conducting tests in the context of INFRAMIX, in order to implement the experiments designed for the project scenarios:

- A vehicle equipped with an ITS-G5 OBU for communication, and an HMI for visualizing the received messages and signs related to the active traffic control strategies. This vehicle does not have any automation function or driving assistance.
- A second vehicle equipped with the latest automation functionalities for driving assistance, The vehicle connects to BMW's Backend system through mounted BMW communication devices to send data and retrieve individual recommendations (e.g. fix a distance gap, adjust speed, or initiate a change of lane).
- 3 vehicles equipped with a TomTom app that visualizes some of the messages and signs (e.g. open/close lane, SAE level per lane, variable speed, and acceleration). The app receives information broadcasted to all highway users, but does not support individualized control strategies. These vehicles also do not have any automation function or driving assistance used for INFRAMIX scenarios.

With this fleet of vehicles, all different settings envisioned for testing and evaluating the scenarios and use cases can be addressed.

A test vehicle enters the dedicated lane

Test vehicles react to messages

Different communication services

Vehicle motorcade during a test

Figure 21. Test site schematic design and functionalities supported

The drivers recruited to participate in the scheduled tests on the Spanish test side adhered to the common recruiting criteria defined in the project, which states that subject drivers should have no prior knowledge of the C-ITS systems involved in the tests, no prior knowledge of the technologies developed in the project or similar projects, and should be recruited from the public, to the extent possible.

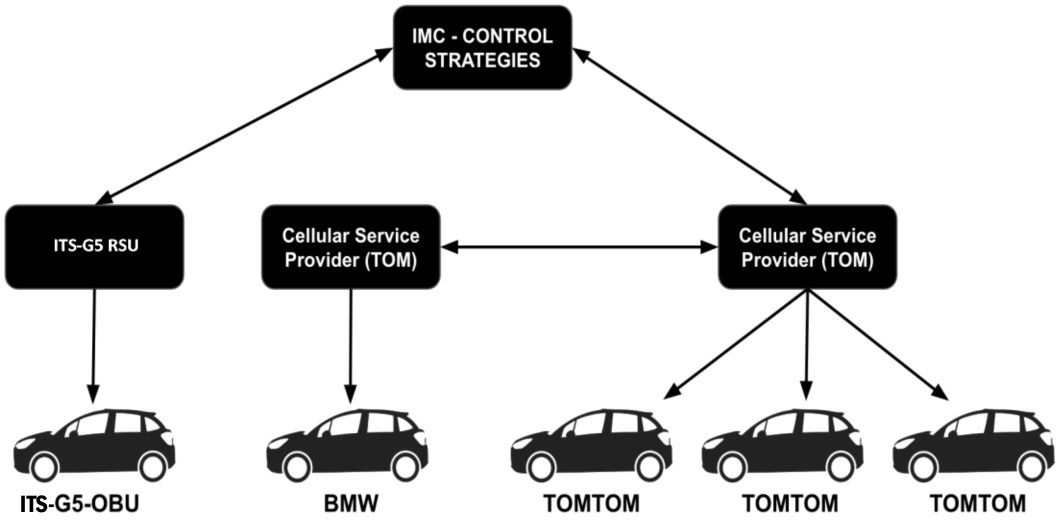


Figure 22. Configuration of the test-vehicles' convoy

5.3 INFRAMIX Test scenarios and use cases - experimental settings

The tests contemplated for the Spanish test site implement the project's three traffic scenarios: dynamic lane assignment, roadworks zones, bottlenecks, and their respective use cases. In the interest of demonstrating these three scenarios of the project, several adaptations and extensions to the test site were made. The scenarios are defined in the project's Requirements Catalogue (D2.1) alongside their particular requirements, including collected data and obtained measurements, traffic management by vehicle type and level of automation, and visual signage and electronic signals exchanged in each case.

Dynamic(Dedicated) lane assignment scenario: aims to test the impact of introducing a dedicated lane for autonomous vehicles on traffic flow, which includes acceptance and appreciation of the new INFRAMIX road signs related to dedicated lanes displayed on digital panels, vertical road signs, and painted road marking. The experimental settings of this scenario consist of inducing a mixed traffic on normal multilane highway segments, without tunnels, lane drops, or entry/exit ramps. A dedicated lane can be dynamically activated and assigned in order to reduce safety concerns related to interference of the circulating automated vehicles with conventional traffic, while balancing the mixed traffic and maintaining its throughput at a level comparable to current traffic throughput for conventional vehicles.

Roadwork zones scenario: aims to evaluate how the infrastructure can help vehicles navigate safety hotspots where the risk of accidents is accentuated by roadworks and onsite staff activities. The experimental settings in this scenario introduce a lane closure for maintenance work on the highway. Efficient and safe guidance is then provided to mixed traffic passing through the roadworks zone. In addition to using traditional visual signs and other physical elements (e.g. cones), accurate information is communicated to automated vehicles through electronic signals, and broadcasted to other vehicles that use it to update their HD-maps and/or nomadic devices. The objectives center on using signage (on the gantries, trolley on the hard shoulder, and in-vehicle display systems) to guide traffic effectively and reducing security risks.

Bottlenecks scenario: investigates real-time controllers such as dynamic speed limits, dynamic lane assignment, merge assistance and ramp metering to manage mixed traffic situations at bottlenecks and avoid degradation in traffic flow. In this setting, the highway has a static capacity downstream and consequently the smooth flow of traffic cannot be guaranteed in high traffic. The scenario's experimental settings allow for testing different types of bottlenecks, with different penetration rates of automated vehicles, in order to assess how to improve traffic efficiency and safety (e.g. avoid deadlocks), by managing the distribution of the vehicles across lanes in real-time, to match a pre-specified opportunistic lane distribution schemes, depending on the traffic situation.

5.4 Procedures for conducting scenario-specific tests

In order to implement and evaluate the defined use cases, reference plans for each use case were designed in collaboration with the partners. These are documented in details in D4.2 "Demonstration phase and data delivery report". Each mockup recreates the required settings for a specific use case on the test site in order to perform the associated tests. According to the reference plans' designs, the test vehicles were circulated as a convoy in a specific order: First the ITS-G5 OBU-equipped vehicle, followed by the BMW vehicle, and then the three vehicles equipped with the TOMTOM app. The test convoy starts at the meeting point located at the toll gate of Girona Oest at the north end of the test site, and drives south on the highway towards Barcelona. The convoy then loops back northwards at an intermediate point selected according to use case being tested, and stops at the starting point. These settings sometimes varied to diversify the experimental settings.

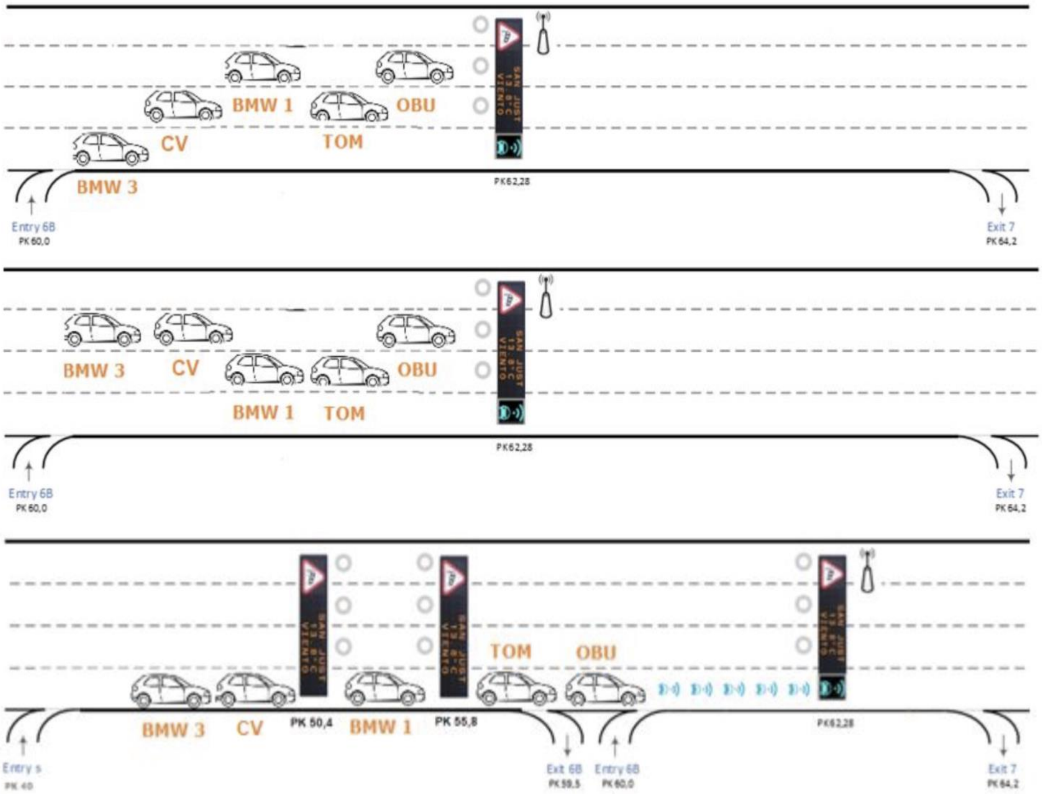


Figure 23. Example of reference plans developed for Dynamic lane assignment

For Scenario 1, Dynamic Lane Assignment (DLA), the dedicated lane pictogram was painted on the rightmost lane of the highway. Traffic information at lane level is gathered by the array of installed magnetometers, and a full-colour VMS was enabled at the start point of the DLA, in addition to the available and operational VMS, which are used to inform drivers about the ongoing test on the highway. Some extra signage and signaling were displayed during the tests as required by the Public Administration in order to guarantee safety. A C-ITS RSU with ITS-G5 has been enabled to provide communication and also validate the hybrid communication infrastructure of the project. Communication with the vehicles are managed at two different highway segments: The detection zone where vehicles receive the dedicated lane warning and additional messages; and the relevance zone where the vehicles should have adapted with respect to the recommendations received.

For Scenario 2, Roadworks, traffic information is gathered in the same manner as in scenario 1. Information related to the roadworks that are taking place in the right lane is displayed in several VMS in anticipation (Roadworks Warning and Speed Limit at 100 km/h), and a trolley, equipped with an additional ITS-G5 RSU, parked at the right shoulder warns the drivers of the proximity of the roadworks zone. With the objective of providing efficient and safe guidance to traffic, accurate information is sent to automated vehicles through electronic signals, and to conventional vehicles through guidance on their nomadic devices, in addition to visual signs and other physical elements. Communication with vehicles is also organized similarly to Scenario 1: In the detection zone, the vehicles receive information about the roadworks warning and additional messages: and in the relevance zone, the vehicles should have adapted with respect to the commands and recommendations received previously.

For Scenario 3, Bottlenecks, the use of the infrastructure is relatively more intensive due to the variety of applied control measures on different vehicles to avoid traffic flow degradation, while monitoring how the mixed traffic is responding. Communication with vehicles is organized in a more elaborate ways compared to the previous two scenarios. Four segments are defined (represented in the following figure 24): Segment 4 is where the traffic bottleneck happens; Segment 2 is located further upstream and is where speed-limit control is applied; Segment 3 is used to accelerate and reach Segment 4; finally Segment 1 was used as a safety area that decreases speed limits gradually as vehicle approach the control area (Segment 2).

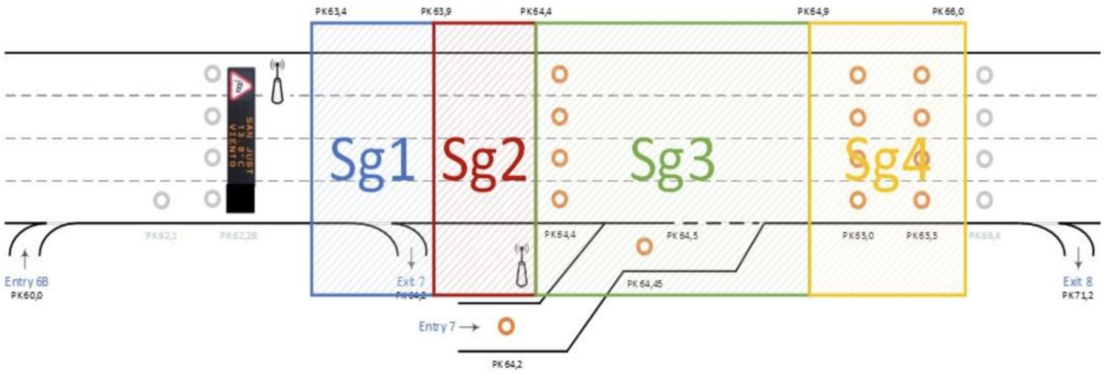


Figure 24. Detection and Relevance Zones in Scenario 3

5.5 Evaluation and assessment activities

As shown in the previous subsections, the setup of the Spanish test site is capable of supporting tests that demonstrate bi-directional communication between infrastructure and vehicles in real settings, and consequently validate the complete information chain among all actors. Moreover, the Spanish site has a good basis for conducting evaluations of traffic efficiency (where microscopic models prevail), using the lane-based data collected in real-time, offering a detailed description of the behaviour of vehicles in mixed traffic situations. The provided traffic data includes real-time information regarding the number of vehicles, the speed of each, time gap between vehicles on each lane, and type of vehicle. The data is stored in Autopistas' cloud-based data storage system

In addition, all tests are followed by questionnaires that solicited to clarify the drivers' reactions to and opinion about the evaluated infrastructure developments (new visual signs, wireless messages recommendations, etc.) in relevant driving situations under real traffic settings. Evaluated indicators of the overall information chain relevant to users' appreciation include comprehensibility, controllability, intuitiveness, learnability, willingness to use, perceived usefulness, and expected impacts. In order to crosslink the user appreciation with the user's background, data was collected on the subjects' background, including driving expertise, age range, etc.

6. Evaluation Setup in real-world: Hybrid Testing

The detailed description of the Hybrid Testing can be found in Deliverable 4.2 *Demonstration phase and data delivery report*, this is a short summary for a better understanding of this document. The evaluation setup for Hybrid Testing embarced a software and a hardware part. On software side, for simulation modelling and for Hybrid Testing, two map files (OpenDRIVE-file and SUMO net file) of the proving ground were required. To start mapping, a local reference measurement was done at ÖAMTC. Previous project work showed that a rectangular measurement of two straight road segments delivers satisfying results for the modelling requirements. After the measurement, the OpenDRIVE-file was created semi-automatically based on OpenStreetMaps™ and Google Maps™. Figure 25 shows the test area as satellite picture and the corresponding SUMO net file. The results from the reference measurement was then used to properly scale and verify the drawn OpenDRIVE-file. Once the open drive file is generated, the SUMO net file can be created. Therefore, SUMO provides a converter. It enables the conversion of open drive files directly into SUMO net file.

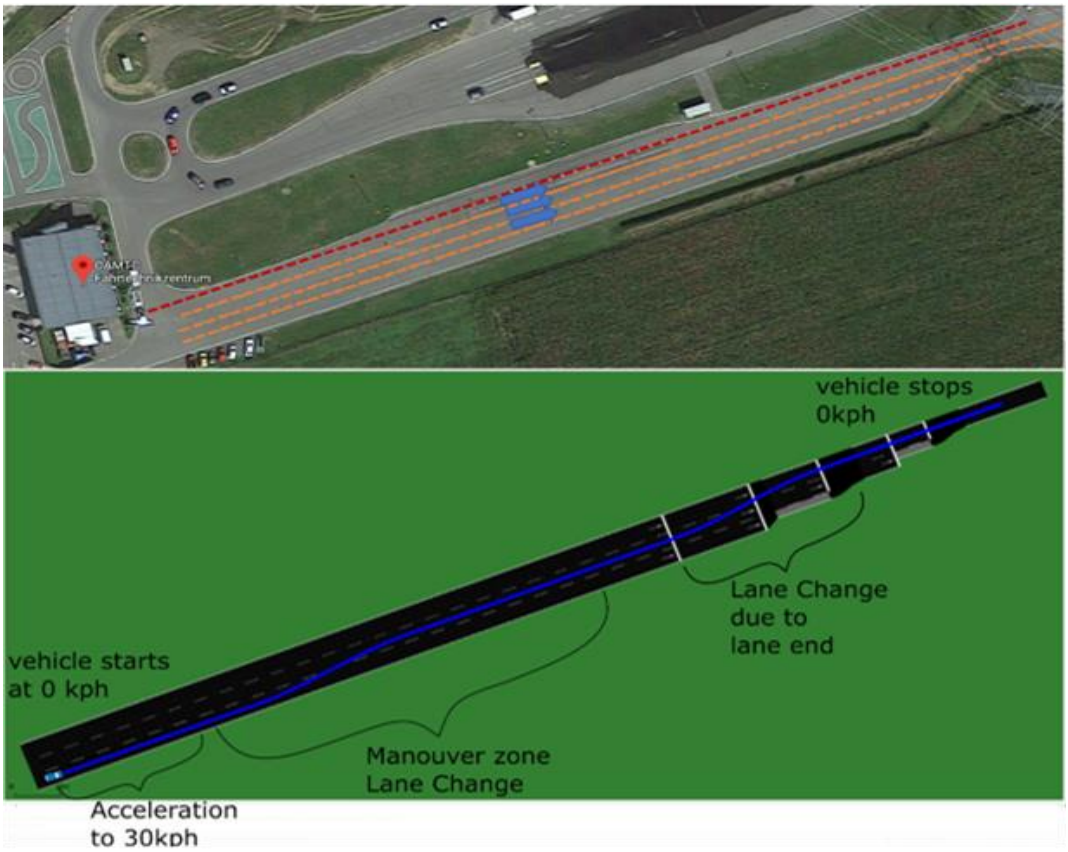


Figure 25. Hybrid Testing Mapping: Manoeuver Zone Satellite Picture & SUMO net file

The simulation framework was parametrized for different scenarios, which are described later in this deliverable. The parametrization needed to be prepared and tested in an office environment (sub-microscopic cosimulation) before conduction real world test.

As lined out at the beginning of this section, a software and a hardware part needed to be prepared. On hardwareside, some hard ware components needed to be integrated to the test vehicle. In the developed Hybrid Testing solution, a real-life automated vehicle (AV), which is a generic automated drive demonstrator and development platform from VIF, is used. The automated driving function, is an in-house developed SAE Level 3 ADAS function with lateral and longitudinal tracking as well as lane change decision capabilities (i.e., Motorway Chauffeur or MWC) enabling the AV to have adaptive cruise control (ACC), lane keeping assistance (LKA) and trajectory planning (TP) functionalities.

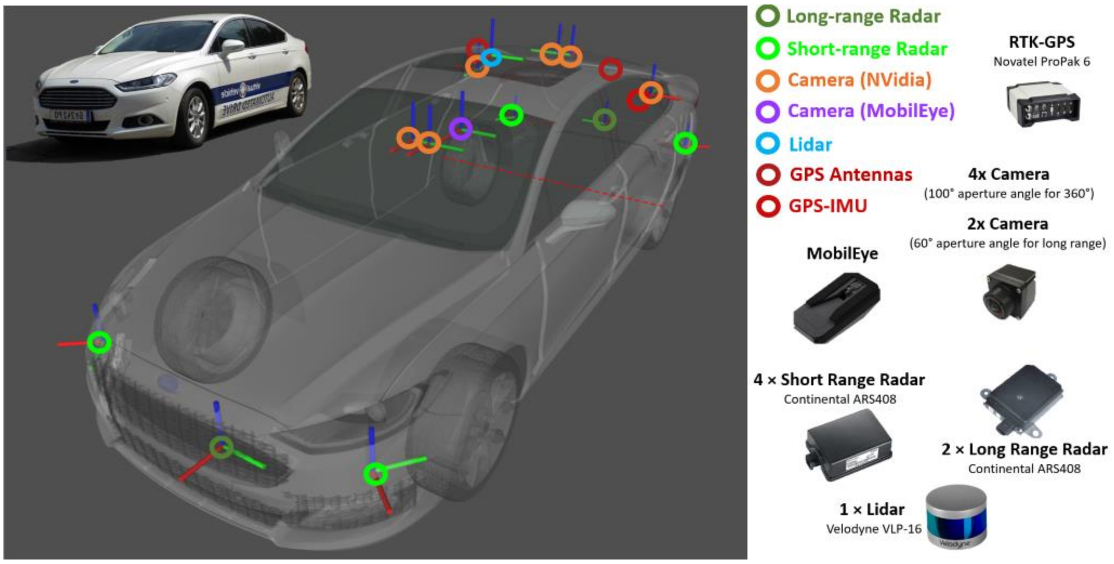


Figure 26. Virtual Vehicle AV Demonstrator vehicle and additional perception sensors

The Ford Mondeo MY2016 AV test vehicle with a hybrid powertrain utilized for the Hybrid Testing implementation along with the additional on-board sensor hardware is seen in Figure 26. Among the indicated sensors in Figure 26, only the dual antenna RTK-GPS is utilized in the scope of the Hybrid Testing. The test vehicle also has many computational hardware for the implementation, where most of the development ECUs are installed at the trunk of the vehicle. The trunk layout is shown in Figure 27 below where numbered items indicate the specific components. Of primary importance in this list is the DataSpeed CAN interface which enables the access to the on-board vehicular sensors and controls of the vehicle. Using this interface, the throttle, brake and steering as well as other parameters can be controlled using a secondary ECU. The data rates for the control specific parameters provided by the DataSpeed CAN interface can be seen in Table 6.

1.	dSpace MicroAutoBox-II (ds1401) realtime ECU
2.	PC Nuvo – 7006 E-PoE PC
3.	Dataspeed CAN and Power distrubution interface
4.	Network switch
5.	W-Lan Router
6.	Power inverter (DC-AC)
7.	USB Multiplexer
8.	Aurix Safety Gateway
9.	Nvidia Drive PX2 ADAS PC
10.	HDMI Multiplexer
11.	High Precision RTK-GPS (Novatel ProPak6)
12.	Inertial Measurement Unit (Novatel IMU-IGM-S1)

Figure 27. Ford Mondeo AV demonstrator computational hardware at the trunk compartment

Table 6. DataSpeed CAN data and the corresponding data rates

Feature	Ford Fusion
Platform	FORD CD4
Initial release date	Oct 2015
Throttle control frequency	50 Hz
Brake control frequency	50 Hz
Steering control frequency	100 Hz
Steering angle control	Yes
Steering torque control	No
Gear shift control (PRNDL)	Yes[1]
Turn signal control	Yes
ULC (speed control)	Yes
Individual wheel speeds	100 Hz
3-Axis accelerometer	100 Hz
Roll and yaw rate gyro	100 Hz
Parking SONAR sensors	5 Hz
Tire pressures	2 Hz
GPS	100 Hz

The test vehicle also houses a dSPACE MicroAutobox-II (ds1401) real time ECU that runs the ADAS functions in real time based on the provided sensor data from on-board sensors as well as the simulated one from the co-simulation platform. The ADAS functions for ACC, LKA and TP are implemented in MATLAB/Simulink and later exported to C++ code, that is automatically generated by the MATLAB/Simulink embedded coders to run on the dSPACE MicroAutobox real time hardware. So, the ADAS functions running on the MicroAutobox ECU send driving commands to the actuators through the DataSpeed CAN interface so control the vehicle. In oder to reveice C-ITS messages, an OBU/RSU was mounted on the vehicle during tests.

For the evaluation, described later in this deliverable, the described hard- and software components then had to interlock intelligently during testing.

7. Evaluation Results

The impact on safety and traffic efficiency is mainly evaluated by the means of simulation. However, the results from the driving campaigns have close connection.

The evaluation also regards for communication flows of the designed INFRAMIX system.

7.1 Impact on Safety

For the Austrian road and motorway network the „Kuratorium für Verkehrssicherheit“ [14] issues an annual accident report. Based on the accident numbers of the past years there are some general remarks that should be noted before looking in more detail into the INFRAMIX related numbers.

In general, accident numbers on the motorway are considerably lower than on the lower level road network, only about 6% of the road accidents happen there [10]. This should be kept in mind as our baseline when comparing accident numbers in the following, where we will only speak of the percentages of accidents on the motorways.

7.1.1.Potential analysis based on accident statistics

Before looking deeper into the different types of accidents, it is worth discussing the so-called “suspected reasons” for the accident. It is called “suspected reasons”, because this relies on the assessment of the authority (typically a police officer) recording the accident. This statistic shows clearly that the vast majority (over 75%) of accidents is related to inattentiveness/distraction, insufficient safe distance and inadequate choice of speed. A timely additional information via C-ITS INFRAMIX messages can very likely address the issue of inattentiveness and there are INFRAMIX concepts, for example, addressing the safe distance. On the other hand accidents which would require driver monitoring, such as medical problems of the driver or drugs and alcohol related accidents can not be addressed by the INFRAMIX approach.

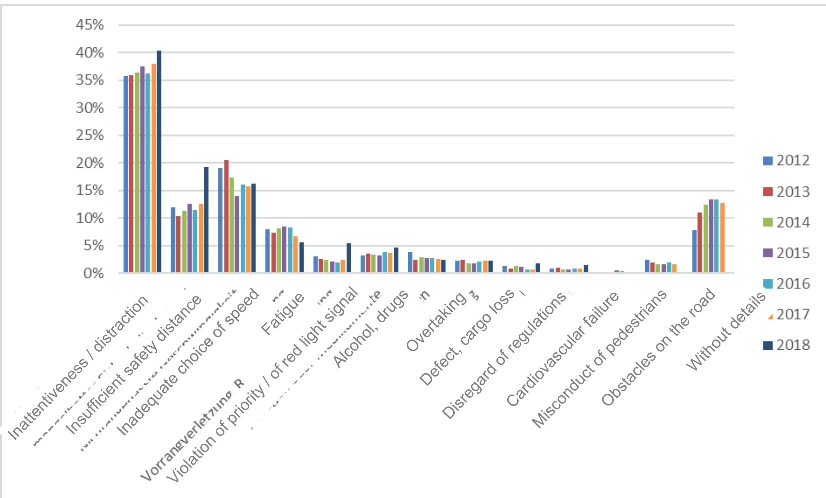


Figure 28. Presumed causes of accidents on the ASFINAG road network. Note that starting from 2018 the bar at "without details" does no longer exist due to a change in the recording system [source: “Unfallgeschehen im ASFINAG-Netz 2018 Wien, Stand 09.07.2019; study conducted on behalf of ASFINAG Service GmbH by KFV Sicherheit-Service GmbH KVI]

7.1.2. Impact assessment approach

In a workshop held by partners BMW, VIF, ASF and SIE it was decided to follow an impact assessment approach based on nine basic impact mechanisms. The basis for the mechanisms was the nine safety impact mechanisms of intelligent transport systems of Kulmala (2010) which were adapted from the mechanisms formulated by Draskóczy et al. (1998)

The purpose of these mechanisms is to ensure that the assessment covers systematically the intended and unintended, direct and indirect, short-term and long-term impacts of both AV-users and non-users. These mechanisms should be used for all impact areas of AD studies. [11], [12]

The 9 mechanisms are defined as follows:

1. Direct modification of the driving task, drive behaviour or travel experience
2. Direct influence by physical and/or digital infrastructure
3. Indirect modification of AV user behaviour
4. Indirect modification of non-user behaviour
5. Modification of interaction between AVs and other road-users
6. Modification of exposure / amount of travel
7. Modification of modal choice
8. Modification of route choice
9. Modification of consequences due to different vehicle design

A further important point addressed in these papers is, that mechanisms should be

[..]non- overlapping and all-inclusive, i.e., that all impacts would fall under some and (preferably) only one mechanism. In cases in which an impact falls under two (or more) mechanisms, it is preferable to select the most suitable one.

Table 7. Impact Mechanisms

Safety Mechanism	Description	Inframix relevance (Effect Descritpion, if any)
1. Direct modification of the driving task, drive behaviour or travel experience	*Related to the change of driving process, actions, habits and style*	INFRAMIX comes from car-outside, see Nr.2
2. Direct influence by physical and/or digital infrastructure	*Direct influence by roadside systems mainly by giving information and advice. Without the possibility to control driver action or the vehicle directly, the impact of this influence is more limited than of the in-vehicle systems. In other aspects the impacts are similar as the ones described in mechanism 1.*	Scenario 1: By creating a Dedicated lane a change in TTC/mean spead can be observed
		Scenario 2: RWZ: By sending C-ITS messages a head of Roadwork tailers, the amount of destroyed trailer shall decrease.
		Scenario 3 Bottleneck: Hypothesis: less critical situations in measure simulation compared to baselie simulation
		Non SC/UC specific influence: "General hazadours warning" with great potential: rear end collisons onto standing or moving vehicles are more than 40% (more than 50% in RWZ) of the accidents. Especially dangerous (according to ASF) are rear end collicions involving trucks. The higher damage by a truck is unquestionable, however, ASF and official numbers do not show a higher accident risk of trucks since the vehicles >3.5t represent roughly 10% of the traffic, but cover 15% of the mileage. Coverage of camera system oft he ASF network: Tunnels 100% (by law) Whole network about 60-70% Permanent >80% in principle. Technology for automatic detection of standing vehicles is being currently tested.

3. Indirect modification of AV user behaviour	*3.Indirect modification of user behaviour in many, largely unknown ways. The driver will always adapt to the changing situation. This behavioural adaptation and will often not appear immediately after a change but may show up later and it is very hard to predict. The indirect modification is more long-term than the very direct, short-term reactions to the system in mechanisms 1 and 2. Long-term behavioural adaptation may appear in many different ways (for example, by reallocation of attention resources, by change of headway in a car following situation, by change of expectation of the behaviour of other road users). This adaptation may frequently be due to delegation of responsibility of the driving task partly or totally to the system, which the drivers have learnt to rely*	An driving mode impact on modal shift Impact is possible (human driven vs. automated). Inframix V2X offers the potential of an extended ODD eg. more automated driving. The Safety layer still lies in the vehilce.
4. Indirect modification of non-user behaviour	*This type of behavioural adaptation is even harder to study because it is often secondary. Non-equipped drivers may for example change their behaviour by imitating the behaviour of equipped drivers (for example, driving closer or faster than they should, not having the equipment). These effects are often evident at the traffic flow level.*	The authors of the paper referred to argue that Non-user are drivers who are not recieving the inframix messages.INFRAMIX aims to provide the messages to all users .(also non-connected via VMS). Also in simulation all cars are informed via VMS. There, we aregue is no NON-user

5. Modification of interaction between AVs and other road-users *+ What are the impacts on interaction (communication, resolution of encounters) between* *between* *the AV and other road users (on links and in intersections)? E.g.,* *+ Between connected AVs* *+ Between connected AV and connected non-AV* *+ Between AV and non-connected vehicles* *+ Between AV and other road users* *+ What are the impacts of the new*	*Modification of interaction between road users. ITS will change the communication between equipped road users. This change of communication may also influence the traditional communication* *with non-equipped road users. To a large extent this problem may appear in the interaction between drivers and unprotected road users.*	Real World tests would be highly interesting. However, the penetration rate of Connected and Connected Automated Vehicles is still too low. Simulation Study: + Human Driver: driver changes lane for cooperative driving + ODD expansion: more %age of automated driving mode (Human/automated split, also see 3) + Highly country dependent
6. Modification of exposure / amount of travel	*Modification of road user exposure by for example information, recommendation, restrictions, debiting. This mechanism covers only changes in the amount of travelling, i.e. whether the road user decides to make more or less, or longer or shorter, trips due to the system. This is an important mechanism for the safety effects as changes in exposure affect the expected number of all crashes, injuries and fatalities*	For a better supported Highway Pilot: + Longer Distance Trips (Workaholic Use Case) + More Leisure Trips

7. Modification of modal choice	*Modification of modal choice by, for example, demand restraints (area access restriction, road pricing, area parking strategies), supply control by modal interchange and other public transport management measures, travel information systems. Different travel modes have different accident risks, therefore any measure which influences modal choice, has also impact on traffic safety.*	The Inframix usecases focus on passenger vehilces on motorways. Other modes of moblilty like trains, planes or public transport is not within the scope of inframix.
8. Modification of route choice	Modification by route diversions, route guidance systems, dynamic route information systems, hazard warning systems monitoring incidents. Different parts of the road network, i.e. different categories of roads, have different accident risks, therefore, any measure which influences route choice by diverting traffic to roads of different category, has also impact on traffic safety. Note that route changes also affect exposure, and the exposure changes due to the route changes can be taken into account either under this mechanism or mechanism 6. Dynamic navigation and route guidance systems aim to guide the users to their destination via the quickest route, which will result in route choice modifications.	BMW developed an AD-Routing that avoids TOR (for example at RWZ). This function only works on paralell Highways, which are not existing in Austria.
9. Modification of accident consequences	*Modification of accident consequences by intelligent injury reducing systems in the vehicle, by quick and accurate crash reporting and call for rescue, by reduced rescue time. Several systems have been shown to affect safety via this mechanism. To give one example, the expected impacts of the European automated in-vehicle emergency call system, i.e. eCall, were studied on the basis of the case reports of road accident investigation teams in Finland.*	No impact as INFRAMIX has no influences on e-Call(already Stat of the art) and on the corridor for emergency vehicle access..

The participants of the workshop went through the different mechanisms discussing the INFRAMIX impacts on each of them as shown in Table 7. For each mode the interpretation in the context of the project and the relevance for INFRAMIX was discussed. Following the approach to select the most suitable mechanism for each impact it was identified that the INFRAMIX approach mainly tackles mechanism 2, and that all INFRAMIX impacts discussed are therefore most suitable to mechanism 2 or if in doubt can be mapped on mechanism 2 rather than on an other one. Table 7 already brakes down the influence onto the different INFRAMIX scenarios but also the impact of the INFRAMIX approach beyond the specific scenarios.

7.1.3 Analysis on the Impact of Safety from a Sub-microscopic Simulation Perspective

When evaluating safety related to a traffic, ideally, real accident data is utilized to analyse the baseline situation. However, in the scope of the project INFRAMIX, traffic scenarios involving mixed automated and conventional vehicles at various penetration rates are analysed, and therefore there is no suitable baseline data available. This is due to the simple fact that there are no, and if exists at all, a very small number of automated vehicles on real roads. Therefore, simulation models need to be built to analyse the baseline situation so that an assessment of the effect of new control strategies can be made. Of particular interest is the assessment of the number of crashes in such mixed-traffic scenarios.

In analysing the number of crashes as a means of assessment for traffic safety for mixed traffic flows, suitable proxies (or KPIs) must be used to measure how many vehicles are in critical situations. This is required since microscopic or sub-microscopic traffic simulation framework implemented in the scope INFRAMIX project cannot model vehicle crashes and specifically their resulting possible effects on the traffic flow. Therefore, we need to resort to specific KPIs to make conclusion on the safety. Two possible KPIs have been considered for the assessment of safety from the perspective of sub-microscopic simulations:

1. Time-to-collision (TTC),
2. Amount of strong braking actions.

Time-to-collision (TTC) is a common measure to characterise critical situations in microscopic traffic simulations. Amount of strong braking manoeuvres on the other hand quantifies the necessary control action to maintain the required distance between two vehicles, and therefore is also considered as an alternative KPI in this study.

The number of vehicles in critical situations are weighted results in accident probabilities. In the end, the statistical probabilities of the baseline and measure simulations have to be compared to arrive at a conclusion about the effect on the traffic safety. In the following subsequent sections both KPIs from the perspective of sub-microscopic simulations are described and the obtained results are discussed.

7.1.3.1 TTC as a safety KPI

In analysing traffic conflicts and safety, TTC is proven to be an effective measure for rating the severity of traffic conflicts and for discriminating critical from normal behaviour. The direct use of TTC as a criterion for decision-making is also a common practice in the traffic control domain. Based on this background, TTC was also a natural choice for a measure or KPI for the assessment of critical traffic situations in microscopic and sub-microscopic simulations. In such simulation studies, TTC must be calculated and evaluated out of the history of relative vehicle positions for every microscopic traffic object (i.e., vehicles) during the simulation.

A good presentation of TTC values for a specific time span is the cumulative frequency as shown in seen in the Figure 29 below.

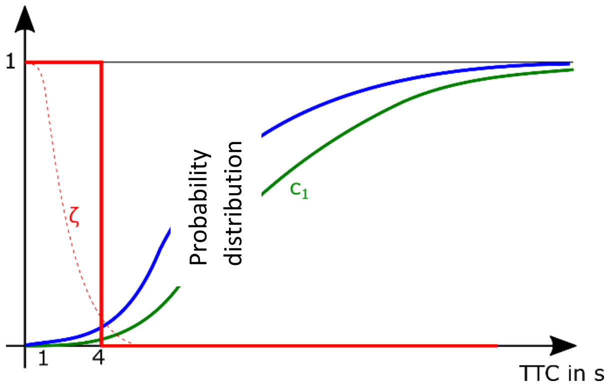


Figure 29. Cumulative frequency of TTCs

In figure 29, the blue curve denoted as the function $c_0(x)$ depicts the cumulative frequency of all TTC values of the baseline simulation (i.e., the simulations without new infrastructure or control measures). The green curve denoted as the function $c_1(x)$ is the cumulative frequency of all TTC values of the measure scenario (simulation with a new infrastructure or control measures, e.g. a speed advice sent via an IVI message). The following formula for the current safety proxy based on TTC, denoted as KPI_{TTC}, describes the cumulative relationship between these two functions and a weighting function ζ(x).

$$KPI_{TTC} = \int_0^\infty \zeta(TTC).\left(c_0(TTC) - c_1(TTC)\right)dTTC$$

Here ζ(x) is a function dependent on the TTC, which weights the sum of these Integral operator is used to obtain a cumulative correlation with the number of accidents. Since the real function ζ(x) variation is not known with certainty, a simple approximation is used. The utilized approximation utilizes a threshold TTC value denoted as TTC_{Th}, and is defined below.

$$\zeta(TTC) = \begin{cases} 1..TTC \leq TTC_{Th} \\ 0..\ TTC > TTC_{Th} \end{cases}$$

7.1.3.1.1 Calculation of TTC in SUMO

Sumo uses *SSM*-files to record critical TTC events. These events belong to situations when the TTC is below a user-defined threshold. Sumo always calculates the TTC of two individual vehicles that are strictly on the same lane. This also applies to the situation when two vehicles drive side-by-side on the same lane. This can, for example, happen during an overtaking manoeuvre. The same situation is often observed in the case of motorcycles since they are very narrow, and they can usually overtake a car without necessarily changing the lane. Therefore, TTC values involving at least one motorcycle (i.e., one road vehicle and one motorcycle) which drive next to each other on the same lane are not considered in the following evaluation. Since the percentage of motorcycles in the simulated traffic is very small, then this exclusion has minimal effect on the overall result.

Regardless of the exclusion of motorcycles in the evaluated traffic, due to the close offset of vehicles during a lane change as depicted in Figure 30, the built-in TTC report in SUMO can result in an unrealistic ratio of TTC values that are either too small or zero. Therefore, this required the implementation for calculating the TTCs below a certain threshold, based on a self-defined function as part of the co-simulation framework. In doing so we use the lateral offset (y_{offset}) as shown in Figure 30, which is the gap between the vehicles involving overtaking manoeuvres for every conflict event. If the gap is more than a pre-set threshold then y_{offset} calculation is ignored for the KPI evaluation.

The lateral gap y_{offset} threshold values were also varied at threshold levels of 0.2m, 0.5m, and 1m. For 0.2m the counts get very low and the curves are not useful. Between 0.5 and 1m there are less differences. In the end y_{offset} threshold of 0.5m was used for the evaluation.

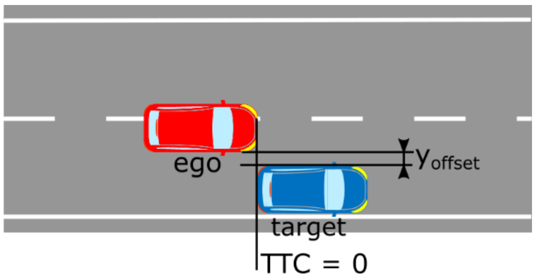


Figure 30. TTC when overtaking and the lateral offset definition used for TTC calculations for critical events

7.1.3.1.2 Evaluation based on KPI_{TTC}

In this subsection, the KPI_{TTC} safety KPI evaluation with a threshold of level of <3 seconds for the TTC is shown and discussed. In what follows, the corresponding results from sub-microscopic simulation analysis is reported in subsequent plots from Figure 31 to Figure 34 for varying traffic density levels (i.e., *LOS-Level of Service*) are given. All the results correspond to the bottleneck scenario (SC3-UC3), where the vehicle under test drives on an onramp to merge to the main motorway (see the deliverable D2.3-"Specification of Submicroscopic Simulation" for a detailed descriptions of this scenario). In the following figures we give the whole cumulative frequency variations of the TTCs on the left-hand side, and the zoomed-out variations up to 3 seconds in the in inset on the right-hand side. These cumulative probabilities are evaluated through the weighting curve. It can be observed that the weighting curve is one as long as the TTC is below 3 seconds, and afterwards it is zero. During the development of the KPI, it was expected by intuition that the cumulative frequency of the baseline (indicated with blue curve) will be higher than the cumulative frequency of the measure scenario. But it can be seen in the figures below, that this is not always the case.

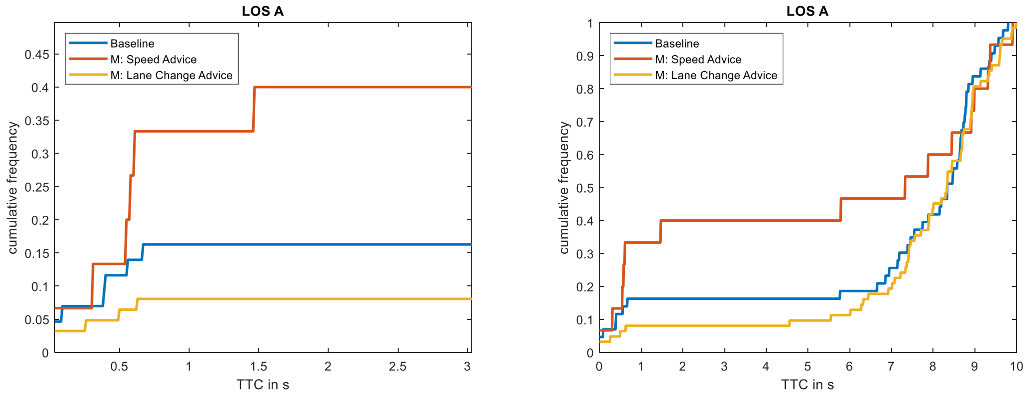


Figure 31. TTC as Safety KPI, BOTTLENECK onramp, for LOS-A

In Figure 31, the evaluation of TTC for LOS-A is illustrated. It is observed that the cumulative frequency of the TTC values of the measure simulation with “speed advice” message is higher than the cumulative frequency of the baseline TTCs. This means that there is a higher risk of an accident. On the other hand, the cumulative frequency of the TTCs of the measure simulations with “lane change advice” is lower. This can consequently be interpreted as a lower safety risk. It can be noticed that there are large (or rough) steps in the cumulative frequency curves, which indicates that there are too less counts contributing to the evolution of the curves.

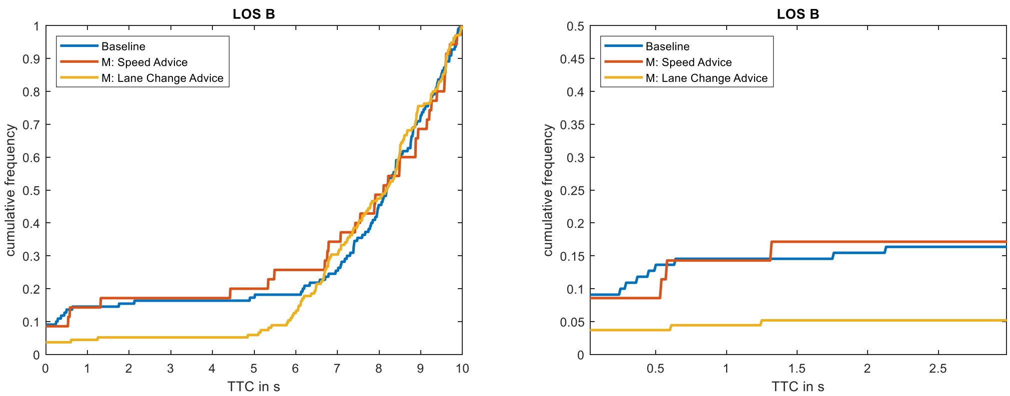


Figure 32. TTC as Safety KPI, BOTTLENECK onramp, for LOS-B

In Figure 32, the results from sub-microscopic simulation analysis for TTC with LOS-B is depicted. The cumulative frequency of TTCs of the “speed advice” message is not significantly far away from the curve of the baseline simulation. Due to the smaller number of contributing events it is difficult to make a statement weather it is an improvement or not, meaning that it is indecisive. In the case of the “lane change advice” message the cumulative frequency of the measure simulation is lower, which is an indicator for an improvement for this traffic density.

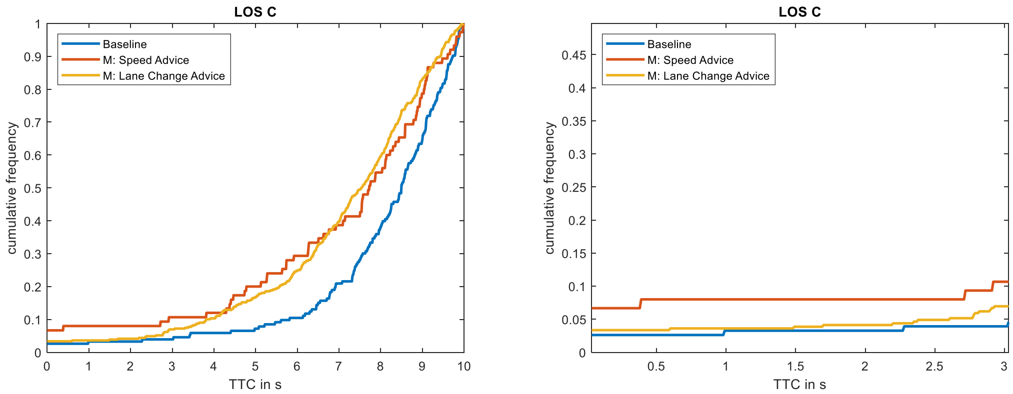


Figure 33. TTC as Safety KPI, BOTTLENECK onramp, for LOS-C

In Figure 33, corresponding to the TTC evaluation for LOS-C, it can be observed that the cumulative frequency of the TTCs in the case of the baseline is lower than the cumulative frequency of the TTCs of the two measure scenarios. Particularly, the TTC for "speed advice" message is clearly higher. This would indicate that the measure scenarios lead to a decrease in the level of safety. But again, the rough steps demonstrate that there are only small number of events contributing to these results, and that a definitive statement regarding safety cannot sufficiently be made on a good basis.

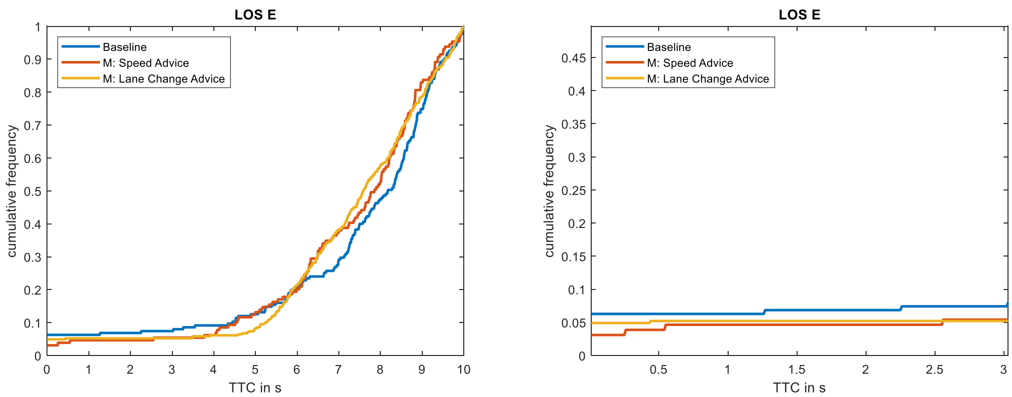


Figure 34. TTC as Safety KPI, Bottleneck onramp, LOS-E

In the case of LOS-E traffic density, where the results are given in Figure 34, the curve of the cumulative frequency of TTCs of the baseline simulation is higher than the curve of the measure simulations. This is an indicator for an improvement due to the measure signals including "speed advice" and "lane change advice". This indicates that infrastructure messages can improve safety, as measured by the TTC at high traffic densities.

Table 8. TTC as Safety KPI, Bottleneck, onramp scenario, evaluation results overview

SC3UC3, Bottleneck, Onramp				
	LOS A	LOS B	LOS C	LOS E
$KPI_{TTC\ 3, Speed\ Advice}$	-52.8 %	-1.2 %	-14.4 %	6.6 %
$KPI_{TTC\ 3, Lane\ Change\ Advice}$	22.1 %	29.2 %	-2.7 %	4.8 %

SC3UC3, Bottleneck, Onramp				
	LOS A	LOS B	LOS C	LOS E
$KPI_{TTC\ 3, Speed\ Advice}$	-52.8 %	-1.2 %	-14.4 %	6.6 %
$KPI_{TTC\ 3, Lane\ Change\ Advice}$	22.1 %	29.2 %	-2.7 %	4.8 %

Table 8 contains an overview of the TTC as a safety KPI for the onramp scenario. As a final remark, it can be concluded that TTC as a safety criterion is not indicating clear trends, at least from the perspective of sub-microscopic simulations, which is mainly due to the low number of contributing TTC events.

The obtained result can be strengthened if a similar analysis can be done with sufficiently long simulation duration and utilizing a sufficient number of vehicles, implying higher LOS values. Given these one can then make a more clear and realistic observations and conclusions based on the simulative results. In the next section, we do same analysis utilizing the same driving scenario (SC3-UC3) but utilizing an alternative KPI based on the quantification of emergency breaking events.

7.1.3.2 Brake rate as a safety KPI

One of the characteristics of the car-following models in SUMO is the aspiration to keep a safe distance to possible leading vehicles. This implies that vehicles tend to brake very often. Therefore, it is obvious that the number of braking events can be used for the assessment of safety traffic situations. This implies that, the higher the number of braking events can be correlated with critical driving conditions and such situation can be classified with higher traffic safety risks. This is represented with the following expression, where c_j denotes the cumulative number of events for which the longitudinal acceleration $\ddot{x}$ is below the threshold value $\ddot{x}_S$.

$$\boldsymbol{c_j} = \sum_{\boldsymbol{i}}^{\boldsymbol{N}} (|\ddot{\boldsymbol{x}}| > |\ddot{\boldsymbol{x}}_{\boldsymbol{S}}|)$$

The relative improvement of traffic safety can be derived by a comparison of a baseline and measure scenarios, where baseline implies the passive traffic and the measure with infrastructure messages involving traffic advices. Therefore, the number of longitudinal accelerations above a certain threshold value can be determined in both situations. We denote number of brake events above a certain threshold with c_B and c_M corresponding to baseline and measure scenario, respectively. The relation between c_B and c_M yields the second safety KPI value that we denote as KPI_{BR} as follows

$$KPI_{BR} = 1 - \frac{c_M}{c_B}$$

7.1.3.2.1 Calculation of brake rate in SUMO

Since the acceleration values are not provided directly by SUMO, these values have to be calculated from the FCD (Floating Car Data). Therefore, it is obvious to calculate the acceleration by differentiation of the velocity for every car in the simulation. As expected, numerical differentiation has some negative side effects. Figure 35 shows an extreme example acceleration data obtained from SUMO FCD clearly indicating unrealistic high peaks and oscillations. Besides the numerical calculation errors, SUMO specific characteristics at junctions as well as further uncertain effects are contributing to these unrealistic acceleration values. For the sake of completeness, it should be mentioned that the simulations are conducted with sampling rate of 100 ms.

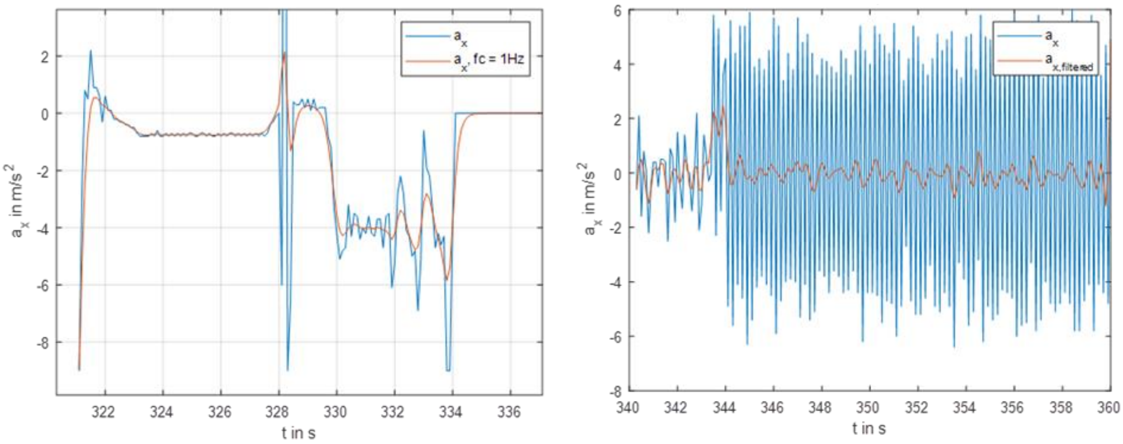


Figure 35. Example single vehicle acceleration data obtained from SUMO

Acceleration signals such as those in Figure 35 cannot obviously be used for further evaluations, particularly for the safety assessment. Therefore, an approach must be applied to obtain more realistic signals such that counting accelerations above a certain threshold makes sense. In general, filtering is a common approach to get rid of undesired peaks, outliers and oscillations in signals. Therefore, the next step was to find appropriate low pass filter parameters as well as a threshold for counting acceleration values above it.

Firstly, different investigations related to filter order were made. This investigation shows that high filter orders lead to overshoots and to multiple counts of acceleration peaks (oscillations). Therefore, a filter of order one was chosen for simplicity. Secondly, different cut-off frequencies were investigated. This was done together with an study of a suitable threshold. The cut-off frequency was varied from 0.5 to 2.5 Hz and the threshold from -10 to -2.5 m/s². As an example, the result of the evaluation for LOS-E can be seen in Figure 36.

The following formula is improved by taking the number of vehicles into account (N_{veh}) in contrast to the former one. Additionally, the average over the total number of experiments (N_{exp}) is calculated.

$$c_{j,exp} = \frac{\sum_i^{N_{veh}}(|\ddot{x}_l| > |\ddot{x}_s|)}{N_{veh}}$$

$$c_j = \frac{\sum_k^{N_{exp}} c_{j,exp}}{N_{exp}}$$

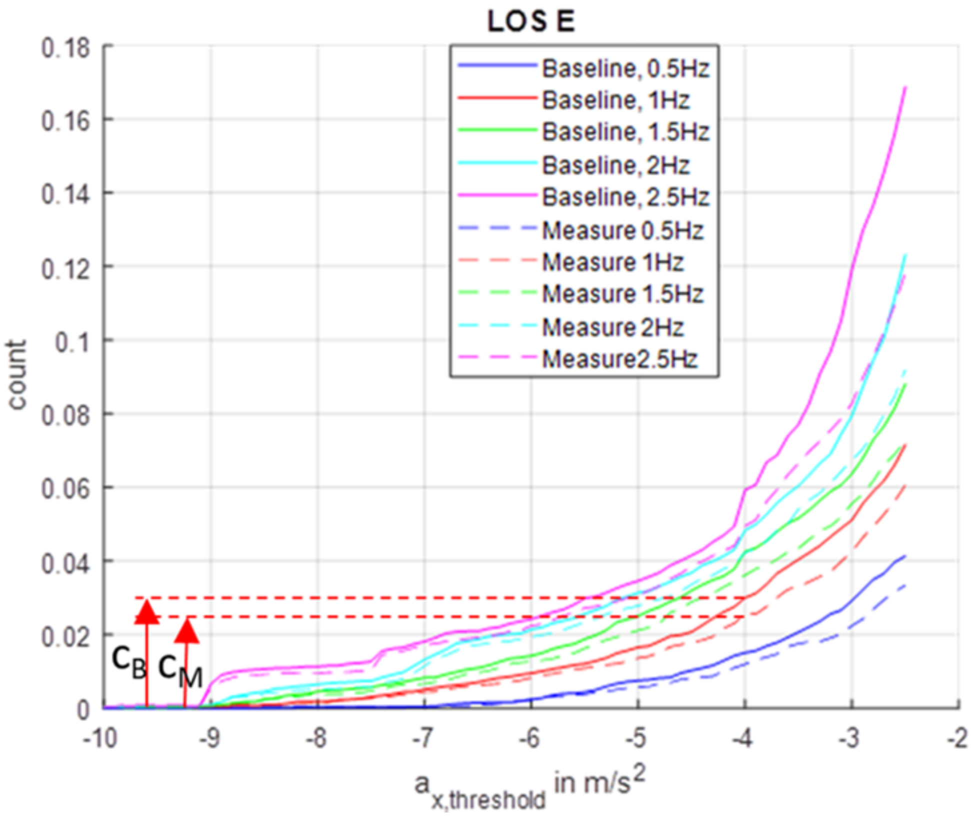


Figure 36. Variation of filter and threshold values for LOS-E class traffic density

After some experimentation, it was decided to use a first order low pass filter with a cut of frequency of 1 *Hz*. The filter was applied in Matlab with the “filtfilt” command, which represents a zero-phase forward-backward filtering method. This choice leads to c_B and c_M indicated in Figure 36.

7.1.3.2.2 Evaluation based on KPI_{BR}

In the following Table 9, the results of the first measure simulation based on “speed advice” are summarized. It is observed that the count of strong brake events has decreased, which is an indicator that the safety has increased in this scenario. In comparison to the results in TTC, brake rate analysis have more consistent trends.

Table 9. Brake rate as Safety KPI, Bottleneck, onramp, speed advice

SC3UC3, Bottleneck, Onramp, Speed Advice				
	LOS A	LOS B	LOS C	LOS E
C_B	0.88 %	2.05 %	2.90 %	3.00 %
C_M	0.86%	0.89 %	1.96 %	2.57%
$KPI_{BR,Speed\ Advice}$	2.7%	56.5%	32.3%	14.3%

On the contrary, in the case of the second measure simulation based on "speed advice + lane change advice" the count of strong brake events has increased significantly as summarized in Table 10. The reason, therefore, is the increasing number of lane changes. The benefit of the lane change advice is, that the rightmost lane is free for merging vehicles coming from the onramp. On the other side, this comes at the cost of a signification increase in the number of lane changes causing more strong braking events

Table 10. Safety KPI, Bottleneck, onramp, lane change advice

SC3UC3, Bottleneck, Onramp, Lane Change Advice				
	LOS A	LOS B	LOS C	LOS E
C_B	0.88 %	2.05 %	2.90 %	3.00 %
C_M	9.14 %	17.06 %	20.08%	14.91 %
$KPI_{BR,\ Lane\ Change\ Advice}$	-932%	-733%	-592%	-397%

7.1.4 Conclusion for the safety analysis from sub-microscopic simulations

The presented analysis is based on a study originating from sub-microscopic simulation framework and focuses in particular on two distinct KPIs that can be used to draw conclusions regarding safety of baseline and measure scenarios. Clearly, the presented results represent a proof-of-concept methodology, which can be extended and further developed.

From the obtained result, it can be concluded that the number of experiments has a big influence on the results, which is strictly restricted in sub-microscopic simulation due to size of the map data and the number of traffic objects available in simulation. Especially, the TTC as a KPI sub-microscopic simulations perspective represents a challenge. The reason is the behavior of the car following and the lane change models in SUMO, and since these always tend to keep a safe distance to a lead vehicle. This fact itself, makes it statistically very difficult to get a reasonable number of TTC values below a specific threshold when the number of experiments is low. While the experiments and the corresponding results do not indicate clear trends, they may also represent the safety risk by introducing new control technologies aiming at reducing a specific problem. This is illustrated in Figure 37, where introducing certain preventative techniques can lead to new accident risks. This in our analysis can be observed in $KPI_{BR,}$ where we observed significant increase in this parameters when "lane change advice" was issued.

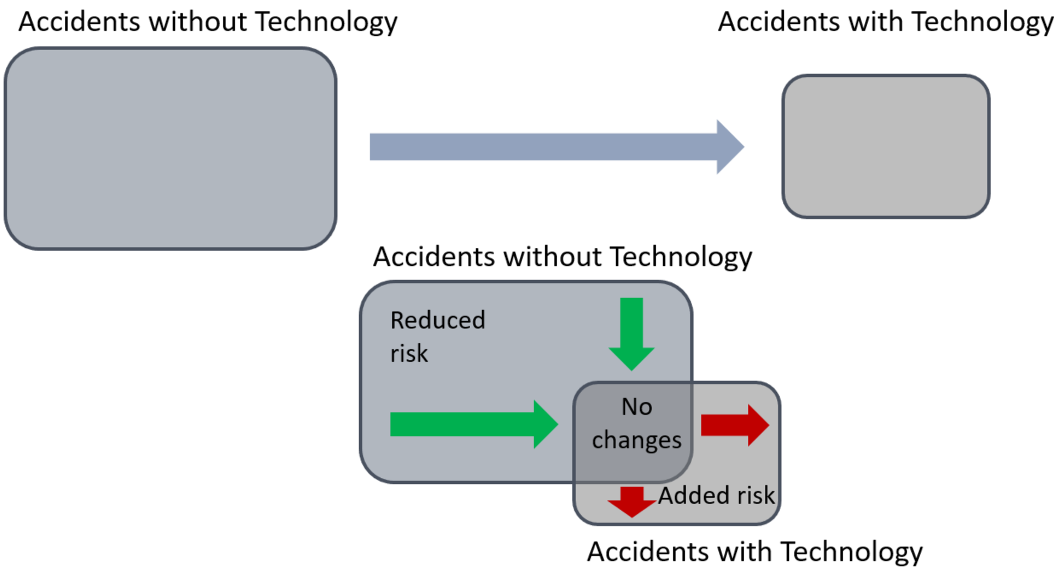


Figure 37. Introduction of technology vs. change of accident risk

The safety conclusions presented here can be strengthened and extended in two clear ways:

1. Perform a similar analysis in microscopic simulation, where TTC frequencies are persistently excited and higher levels of traffic density can be modelled.
2. Utilize the TMC (Traffic Message Centre) that will issue the "traffic advices" (e.g. speed advice and lane change advice) using feedback control.

Therefore, the obtained result can be strengthened if a similar analysis can be done with sufficiently long simulation durations and utilizing a sufficient number of vehicles, implying higher LOS values. Given this, one can then make a more clear and realistic observations and conclusions based on the simulative results.

7.2 Microscopic Simulations Impact on Traffic Efficiency of Bottlenecks

7.2.1 Adaptive cruise control parameters adaptation

The existence of cars equipped with Adaptive Cruise Control (ACC) systems is now a reality, and their use tends to expand in the near future. The ACC systems enable drivers to adjust the desired maximum speed and the desired time-gap to the leading vehicle when following slower vehicles. The ACC systems apply automatically the appropriate acceleration or deceleration of the ACC-equipped vehicle, based on the driver's settings and current measurements. The ACC systems are mainly designed to increase the driving safety and comfort, thus some conservative values for the ACC system settings may be used, i.e. comparatively large time-gaps and low accelerations. Such conservative parameter values, however, may eventually lead to the degradation of the static and dynamic road capacity compared to conventional manual-driving vehicle traffic. The higher the percentage of the ACC-vehicles (penetration rate), the more pronounced will be the influence of their driving modus on the overall traffic flow.

In contrast to the vast literature on ACC and CACC (Cooperative ACC) systems, which focuses on the design, functionality or architecture of these systems, there is a comparatively small number of works which investigate the impact of ACC and CACC systems on traffic flow. These works aim to capture the impact of ACC on traffic flow under different settings (mainly different time-gaps) and penetration rates, using either microscopic simulation or macroscopic approaches. General conclusions that may be drawn from these studies are that: (i) ACC systems have the potential to improve or deteriorate, depending on their settings the traffic conditions compared to the case of conventional manually driven vehicles; and (ii) the level of the influence is closely related to the ACC penetration rate. However, these studies do not systematically examine how the ACC settings should be specified.

A simple but effective ACC-based control strategy has been presented in deliverable 2.5, which aims to adjust in real time the ACC settings of equipped and connected vehicles based on the prevailing traffic conditions. The main philosophy behind the proposed concept is to: (i) leave the ACC-settings untouched at their driver-selected values if traffic flow is clearly under-critical so as to limit interventions only to traffic situations that call for efficiency increase; and (ii) change the ACC-settings gradually as appropriate to improve the flow efficiency when critical traffic states are imminent or present. The proposed control strategy is only dependent on real-time information about the current traffic conditions and is actually activated only when, where and to the extent needed.

For the presentation of the control strategy, consider a motorway with both manually-driven and ACC-vehicles. The ACC-vehicle drivers may introduce their desired ACC system settings, i.e. desired speed, v_d, and minimum time-gap, T_d, but these settings are subject to change if the control strategy recommends or orders different values. The motorway is considered to be divided into segments, and the traffic management centre applies the proposed control strategy at every motorway segment $i=1,2,\ldots$ independently, as illustrated in Figure 38. In particular, at every period (or control interval) t_c, the strategy receives real-time measurements of the exiting flow q_i and mean speed v_i of every segment i. This information may be obtained through conventional spot detectors. The proposed strategy has two goals which are presented below.

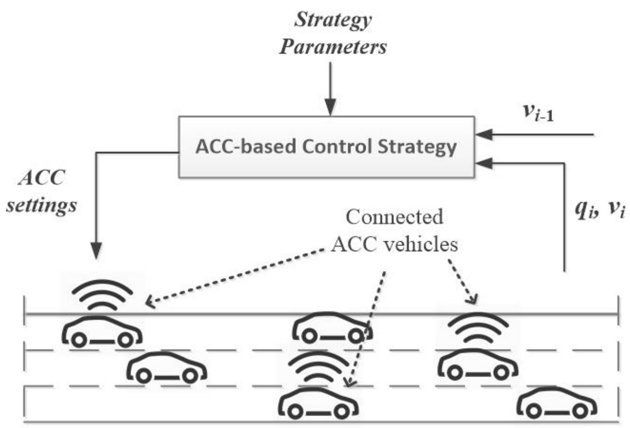


Figure 38. Illustration of the ACC-based control strategy operation for a segment i

The first goal (Model 1) is to determine in real time the time gaps of the ACC vehicles that lead to the increase of the static and dynamic road capacity, where and when it is needed. To achieve this, the strategy gradually decreases the suggested time-gap, when traffic flow is within certain bounds. In particular, the strategy calculates the suggested time-gap as a function of the current segment flow, $T_i[q_i(k)]$, as shown in Figure 39(a). This function implies that, as long as the segment flow is low (i.e. $q_i \leq Q_1$), the maximum time-gap, $T_{\max}$, is suggested, since traffic is not critical. Beyond this lower limit, as the flow increases, the strategy gradually decreases the suggested time-gap value, while for high flow values (i.e. $q_i \geq Q_2$) the strategy suggests the minimum time-gap T_{min}. Note that the suggested time-gap value is reduced to the minimum value before the flow reaches the nominal capacity of the segment. In this way, the strategy aims to delay, or even prevent, the formation of congestion, by maximizing timely the segment's capacity. It should be also noted that the adopted function $T_i[q_i(k)]$ of time-gap versus flow must be decreasing, but can have any form deemed appropriate, e.g. deliver only a (high or low) number of discrete time-gap values, rather than being continuous, as the stepwise function shown in Figure 39(b). It is easy to realize that in this case, higher numbers of discrete gap values would lead to more frequent but less abrupt gap changes for the advancing ACC-vehicles. If, despite the intended capacity increase, the segment becomes congested (e.g. due to even higher arriving demand or due to a shockwave arriving from downstream), then the strategy releases its operation at the congested segments, by suggesting the maximum time-gap $T_{\max}$, for safety reasons. The suggested time-gap will be applied only if it is lower than the individual time gap setting. The above control decisions are summarized by the following equation which determines the suggested time-gap,

$$T_{stg,i} = \begin{cases} T_i\left[q_i\left(k\right)\right] & \text{if } v_i\left(k\right) > v_{cong} \\ T_{\max} & \text{else} \end{cases} \quad (1)$$

where $k = 1,2,\ldots$, is the discrete time index, and v_{cong} indicates the congestion limit. The control strategy decisions are calculated at the IMC and are disseminated to the ACC-vehicles, e.g. via V2I communication. To avoid possible oscillations, the flow measurements are sufficiently smoothed before being used.

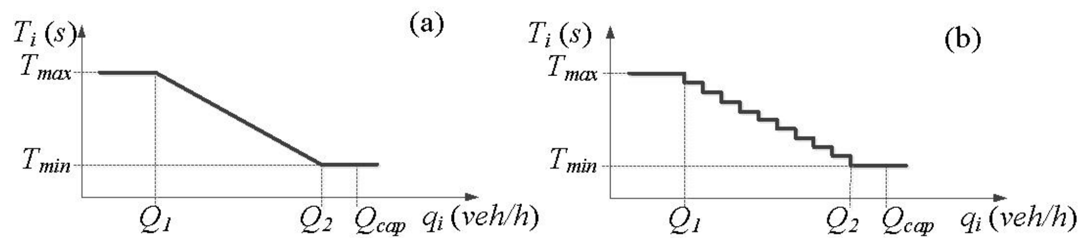


Figure 39. Calculation of the suggested time-gap value using: (a) a linear, or (b) a stepwise function

The second goal (Mode 2) of the proposed control strategy is the maximization of the discharge flow during congestion at the location of active bottlenecks (dynamic capacity). It is empirically known that the discharge flow at the head of a congested area is lower than capacity, and the second goal is to mitigate this capacity drop. The strategy first identifies the location of active bottlenecks. More specifically, if two consecutive segments $i-1$ and i, have a speed difference higher than a threshold Δv, and the mean speed $v_i(k)$ of the downstream segment i is higher than the congestion speed v_{cong}, while the mean speed of the upstream segment, $v_{i-1}(k)$, is lower than v_{cong}, this indicates that these two segments are located just upstream and just downstream of the head of a congested area, i.e. that an active bottleneck has been identified. The discharge flow at the congestion head can be increased by suggesting the minimum time-gap T_{min} applied by ACC vehicles driving within the two mentioned segments. These extended control decisions are implemented via the following relations:

$$\begin{aligned}&\text{If } v_i(k) > v_{cong} \text{ and } v_{i-1}(k) < v_{cong} \text{ and } \left[v_i(k) - v_{i-1}(k)\right] > \Delta v \\ &\text{then } T_{stg,i}(k) = T_{\min} \\ &\text{and } T_{stg,i-1}(k) = T_{\min}\end{aligned} \quad (2)$$

To avoid possible oscillations or false alarms due to moving shock waves, the speed measurements are sufficiently smoothed before being used.

The suggested time-gap $T_{stg,i}$ for each control period is determined by (1) and (2). The ACC-vehicles receive the suggested time-gap, but they apply it only if their individual time-gap setting, $T_{d,j}$, is higher than the time-gap calculated by the controller, i.e.

$$T_{applied,i,j} = \min\left\{T_{d,j}, T_{stg,i}\right\} \quad (3)$$

where $j = 1,2,\ldots$ is the ACC-vehicle index within segment i. Note that the frequency that the advancing ACC-vehicles update their time-gap settings may be higher than at every control interval t_c due to crossing of section boundaries, unless the broadcasting of centrally calculated time-gaps is only effectuated strictly every t_c.

A software tool has been developed within WP2 that implements the control strategy in a generic way. The strategy has now been evaluated using the co-simulation environment for the Spanish test site utilizing a realistic demand profile for the mainstream and a synthetic demand for the most downstream on-ramp. The full population of vehicles includes the following groups: (slow/fast) cars (vehicles), trailers and motorcycles. The user is able to easily modify the penetration rate for CVs (conventional vehicles), CCVs (connected conventional vehicles) and AVs (automated vehicles) among all vehicles. CCVs and AVs are assumed to be equipped with ACC systems. Any suggested time-gap is applied according to (3) by the AVs and the CCVs. AVs apply the suggested values, if needed, immediately while CCVs apply them with a delay. All configuration parameters for the controller are given by the user through an input file.

Apart from the no-control scenario, four control scenarios are defined using various penetration rates for each one of them: two scenarios with time gap adaptation applying only the first goal (capacity increase); and two scenarios with time gap adaptation applying both goals (capacity increase and discharge rate increase). Ten replications are conducted for each scenario and for each penetration rate for a simulation horizon of 3 hours. Each replication has the same average demand profile and the same mean values for all vehicle-related parameters.

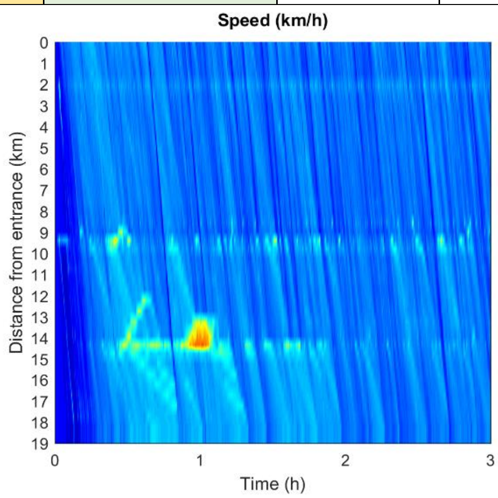
For each scenario and each penetration rate, one replication with results close to the average result of the ten replications is selected for presentation in the following. The simulation results demonstrate that the proposed strategy improves the motorway traffic flow efficiency significantly, even for low ACC penetration rates, compared to the case where the ACC-equipped vehicles are driving with their initial, default ACC settings.

7.2.1.1 Scenario 0: No-control

For the no-control scenario, vehicles are using a range of different default time-gap values. These are 1.1 sec for slow CVs and CCVs, 0.9 sec for fast CVs and CCVs, 1.4 sec for slow AVs and 1.4 for fast AVs. *Table 11*presents the average (over all replications) vehicle delay for each one of the groups of vehicles as well the weighted mean over all groups for all penetration rates (CV-CCV-AV) considered. It can be observed that an increase of the penetration rate for the ACC equipped vehicles, i.e. for CCVs and AVs, leads to an increase of the delays. *Figure 40* presents the speed contour plots, considering various penetration rates, for the no-control case. It can be observed that the conservative time-gap values lead to a strong congestion proportional to the penetration rates.

Table 11. Vehicle delay for the no-control case

Vehicle Delay (s)		Penetration Rates				
		94-4-2	85-10-5	70-20-10	55-30-15	30-45-25
GROUPS	AV	95.3	116.0	142.7	165.7	215.1
	CCV	141.1	145.0	163.3	181.9	221.8
	CT	29.0	29.3	39.6	48.9	81.3
	CV	141.8	144.9	162.9	181.8	221.8
	Motorcycle	98.6	100.2	123.1	129.5	181.6
	Weighted Mean	132.8	135.3	152.4	170.1	210.4



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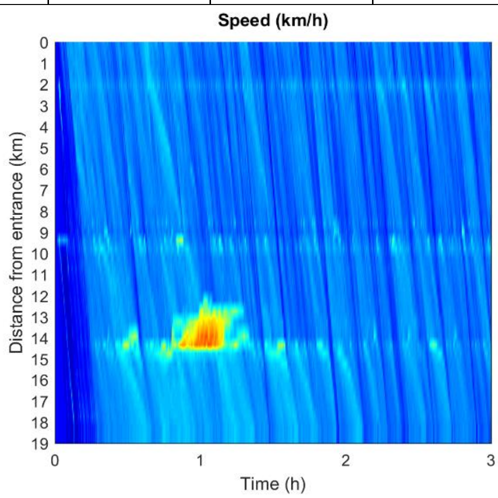

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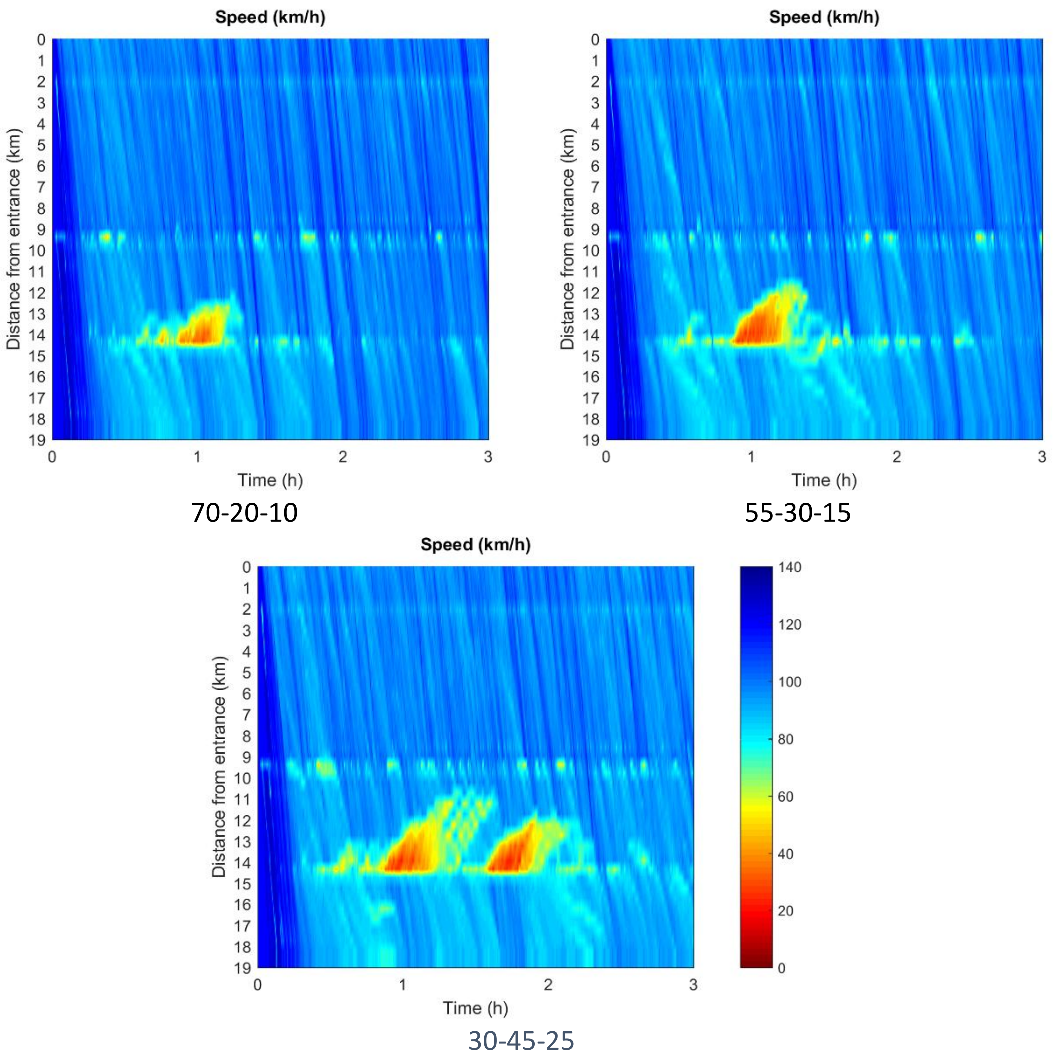


Figure 40. Spatio-temporal diagrams of speed considering various penetration rates for the no-control scenario

7.2.1.2 Scenario 1: Time gap adaptation for Mode 1 with $T_{min} = 1.0$ s

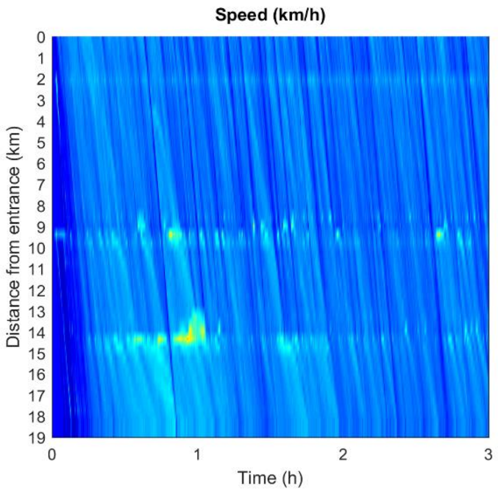
In this scenario, time gap adaptation is applied utilising only relations (1) and (3) in order to achieve the first goal of capacity increase. The control strategy is activated every $t_c = 30$ s, receiving real-time measurements of flow and speed for every segment of the motorway. Exponentially smoothed measurements have been used in order to avoid possible oscillations or false alarms.

The parameters involved in the strategy equations are set as follows: $v_{cong} = 50$ km/h, $T_{min} = 1.0$ s, $T_{max} = 1.4$ s, $Q_1 = 1200$ veh/h/lane, $Q_2 = 1800$ veh/h/lane. The strategy calculates the suggested time-gap T_{stg} using a stepwise function with 3 steps and values from the range [1.0, 1.4] s. The ACC-vehicles receive, every simulation step, the strategy's decisions and update their individual time-gap setting.

Table 12 presents the vehicle delay improvement for each one of the groups of vehicles as well for the weighted mean over all groups for all penetration rates considered. It can be observed that the control strategy achieves significant improvements, especially for high penetration rates. *Figure 41* presents the speed contour plots, considering various penetration rates. It can be observed that congestion has been removed, especially for high penetration rates.

Table 12. Vehicle delay improvement over the no-control case for Scenario 1

Vehicle Delay Improvement		Penetration Rates				
		94-4-2	85-10-5	70-20-10	55-30-15	30-45-25
GROUPS	AV	9.6%	9.2%	19.7%	25.5%	39.9%
	CCV	4.0%	5.8%	14.9%	22.5%	37.7%
	CT	4.7%	1.3%	26.2%	29.5%	59.9%
	CV	3.6%	5.8%	14.8%	22.4%	37.6%
	Motorcycle	6.1%	12.0%	24.3%	31.0%	51.9%
	Weighted Mean	3.8%	5.9%	15.6%	23.1%	39.0%



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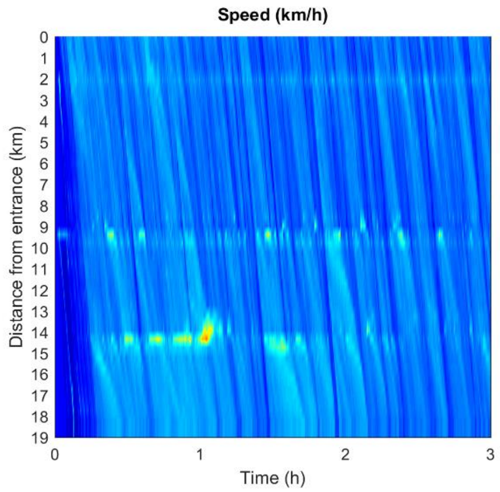

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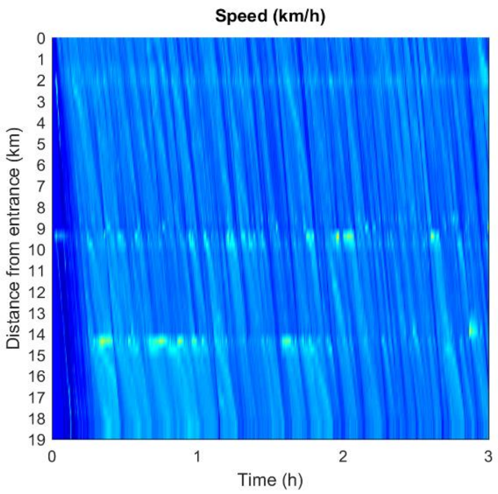

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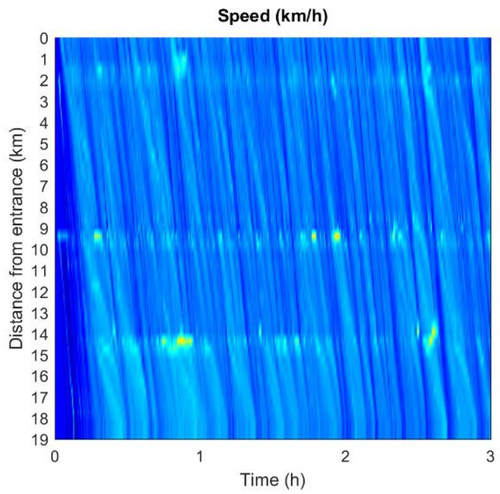

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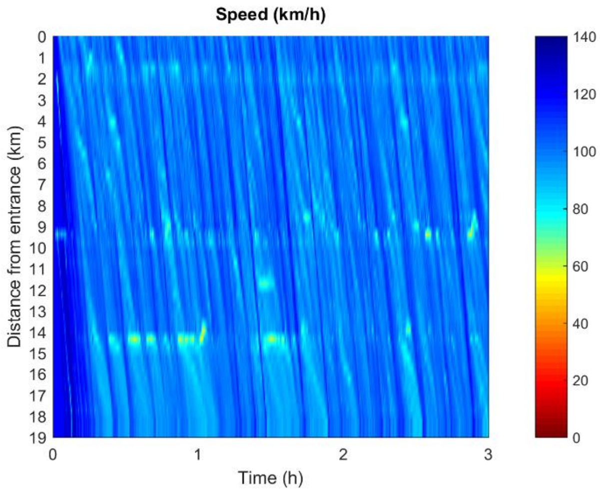


30-45-25

Figure 41. Spatio-temporal diagrams of speed considering various penetration rates for Scenario 1

7.2.1.3 Scenario 2: Time gap adaptation for Mode 1 with $T_{min} = 0.8$ s

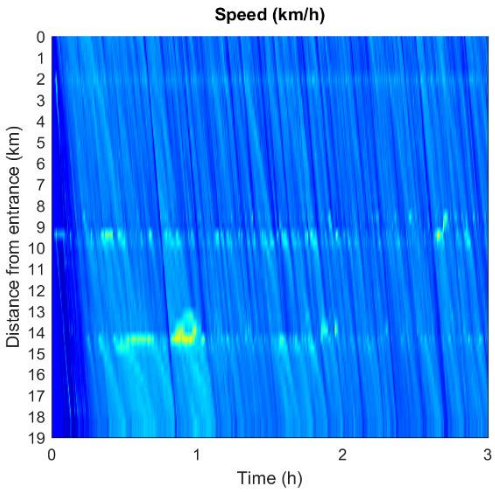
This scenario differs from scenario 1 as a smaller minimum time-gap, $T_{min} = 0.8$ s, is now utilised.

Table 13 presents the vehicle delay improvement for each one of the groups of vehicles as well for the weighted mean over all groups for all penetration rates considered. It can be observed that the control strategy achieves significant improvements, especially for high penetration rates. These improvements are higher compared to Scenario 1 (see also *Figure 45* for a bar chart representation of delay improvements for all scenarios).

Figure 42 presents the speed contour plots, considering various penetration rates. It can be observed that congestion has been removed, especially for high penetration rates. Also, the speed values are a bit higher compared to Scenario 1 (see also *Figure 47* for a bar chart representation of harmonic speed improvements for all scenarios).

Table 13. Vehicle delay improvement over the no-control case for Scenario 2

Vehicle Delay Improvement		Penetration Rates				
		94-4-2	85-10-5	70-20-10	55-30-15	30-45-25
GROUPS	AV	15.3%	17.6%	31.7%	40.2%	53.2%
	CCV	8.0%	14.1%	26.3%	36.1%	51.2%
	CT	6.8%	10.3%	35.3%	40.6%	65.8%
	CV	6.0%	12.2%	24.7%	34.6%	50.2%
	Motorcycle	8.0%	19.6%	37.9%	45.9%	64.7%
	Weighted Mean	6.2%	12.7%	26.0%	36.1%	52.0%



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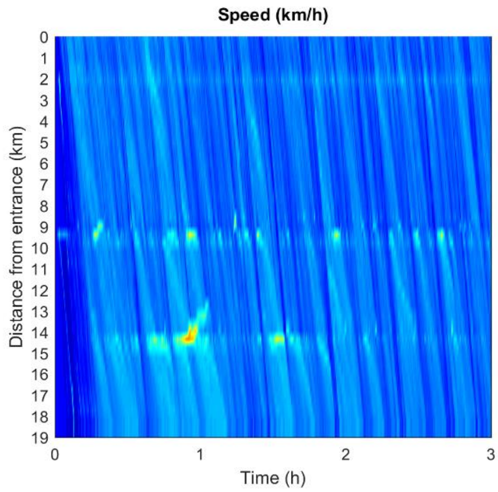

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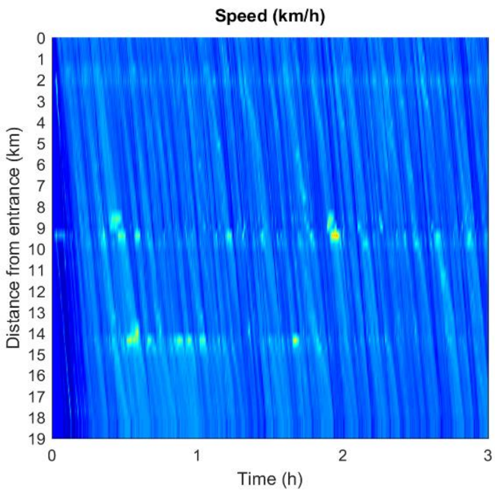

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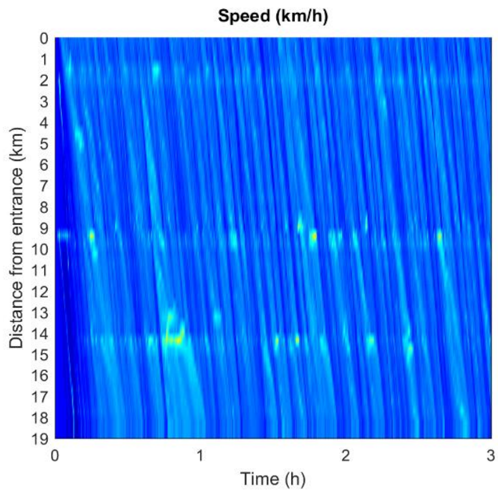
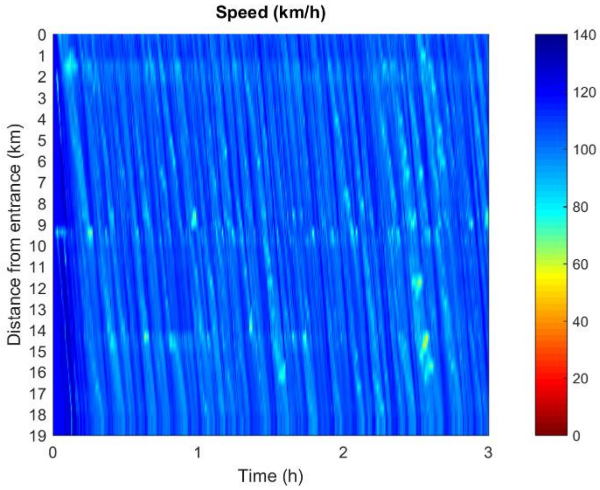


55-30-15



30-45-25

Figure 42. Spatio-temporal diagrams of speed considering various penetration rates for Scenario 2

7.2.1.4 Scenario 3: Time gap adaptation for Mode 2 with $T_{min} = 1.0$ s

In this scenario, time gap adaptation is applied utilising relations (1), (2) and (3) in order to achieve both goals, i.e. capacity increase and discharge flow rate increase. The additional parameter Δv was set equal to 10 km/h. All other settings are those used in Scenario1.

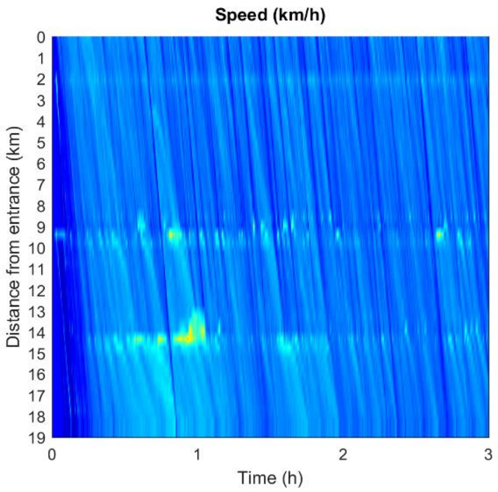
It should be noted that, with these parameter settings, the conditions employed in relation (2) identify the active bottleneck promptly and robustly.

Table 14 presents the vehicle delay improvement for each one of the groups of vehicles as well for the weighted mean over all groups for all penetration rates considered. It can be observed that the control strategy achieves significant improvements, especially for high penetration rates. These improvements are higher compared to Scenario 1, where only the first goal of capacity increase (Mode 1) was applied (see also *Figure 45* for a bar chart representation of delay improvements for all scenarios).

Figure 43 presents the speed contour plots, considering various penetration rates. It can be observed that congestion has been removed, especially for high penetration rates. Also, the speed values are a bit higher compared to Scenario 1 (see also *Figure 47* for a bar chart representation of harmonic speed improvements for all scenarios).

Table 14. Vehicle delay improvement over the no-control case for Scenario 3

Vehicle Delay Improvement		Penetration Rates				
		94-4-2	85-10-5	70-20-10	55-30-15	30-45-25
GROUPS	AV	10.1%	11.2%	21.5%	31.1%	43.2%
	CCV	4.3%	7.4%	16.6%	27.5%	41.2%
	CT	5.3%	8.8%	31.5%	44.5%	67.8%
	CV	3.9%	7.3%	16.5%	27.3%	41.1%
	Motorcycle	6.5%	13.9%	26.7%	37.2%	55.5%
	Weighted Mean	4.1%	7.6%	17.4%	28.3%	42.5%



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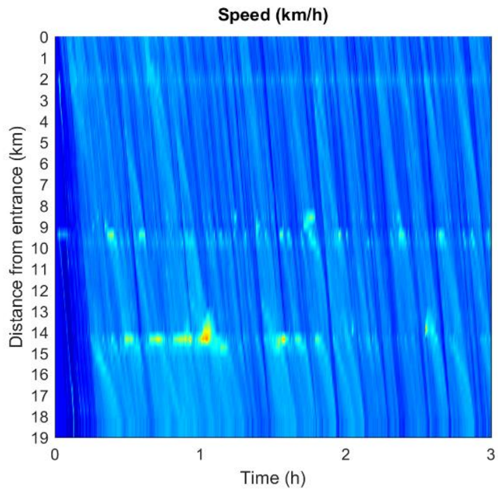

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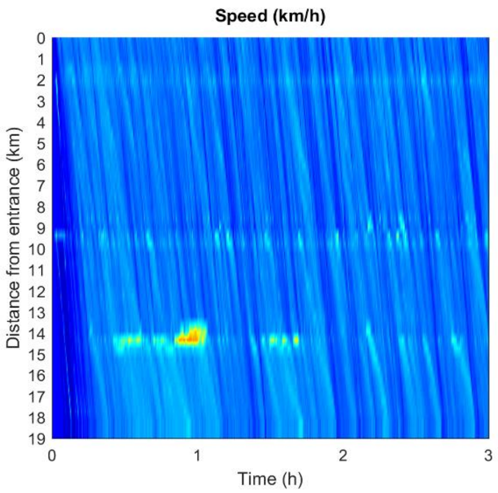

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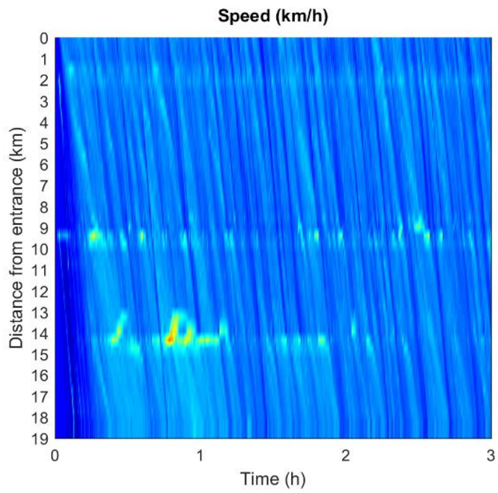

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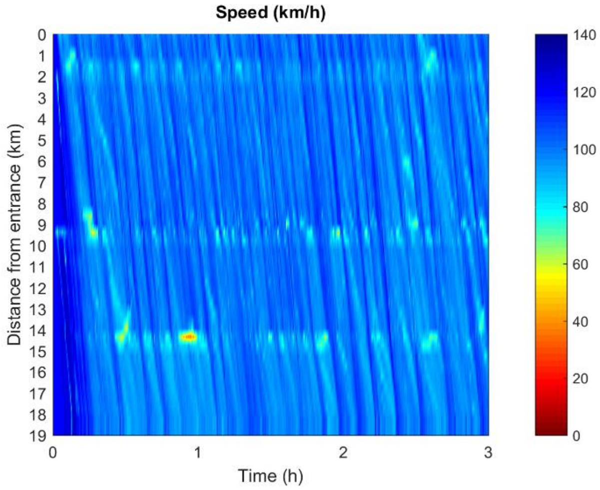

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Figure 43. Spatio-temporal diagrams of speed considering various penetration rates for Scenario 3

7.2.1.5 Scenario 4: Time gap adaptation for Mode 2 with $T_{min} = 0.8$ s

This scenario differs from scenario 3 as a smaller minimum time-gap, $T_{min} = 0.8$ s, is now utilised. *Table 15* presents the vehicle delay improvement for each one of the groups of vehicles as well for the weighted mean over all groups for all penetration rates considered. It can be observed that the control strategy achieves significant improvements, especially for high penetration rates. These improvements are higher compared to all previous scenarios (see also *Figure 45* for a bar chart representation of delay improvements for all scenarios).

Figure 44 presents the speed contour plots, considering various penetration rates. It can be observed that congestion has been removed, especially for high penetration rates. Also, the speed values are a bit higher compared to all previous scenarios (see also *Figure 47* for a bar chart representation of harmonic speed improvements for all scenarios).

Table 15. Vehicle delay improvement over the no-control case for Scenario 4

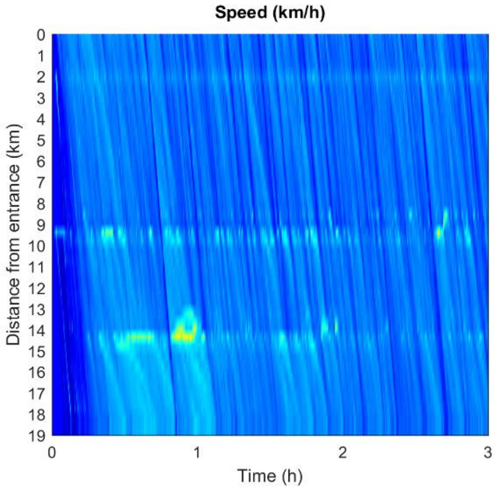
Vehicle Delay Improvement		**Penetration Rates**				
		94-4-2	**85-10-5**	**70-20-10**	**55-30-15**	**30-45-25**
GROUPS	**AV**	**15.7%**	**18.6%**	**33.0%**	**44.1%**	**54.6%**
	CCV	**8.1%**	**15.0%**	**27.3%**	**39.9%**	**52.6%**
	CT	**8.2%**	**13.7%**	**39.1%**	**52.3%**	**71.2%**
	CV	**6.1%**	**13.1%**	**25.8%**	**38.5%**	**51.6%**
	Motorcycle	**8.3%**	**20.9%**	**39.6%**	**50.6%**	**66.4%**
	Weighted Mean	**6.4%**	**13.6%**	**27.2%**	**40.1%**	**53.5%**

7.2.1.6 Some concluding remarks

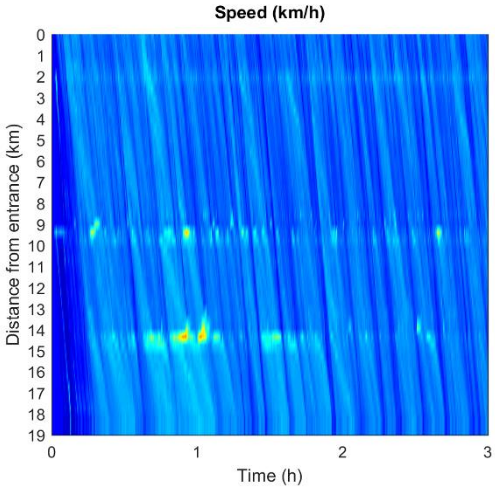
Up to this point only delay improvements have been presented in tables for all groups of vehicles. *Figure 45* presents a bar chart representation of delay (weighted mean over all groups) improvements for all scenarios. Similar positive conclusions can be drawn by looking at the corresponding values and improvements for a lot of other performance indexes. As an example, *Figure 46* presents a bar chart representation of average travel time (weighted mean over all groups) improvements for all scenarios, while *Figure 47* presents a bar chart representation of harmonic speed improvements for all scenarios. At this point we need to note that improvements reported for lower penetration rates are low due to the fact that the controller has to handle easier cases with less congestion observed in the corresponding no-control scenarios. In all cases, congestion phenomena are removed.

All the above simulations and the corresponding conclusions have been produced assuming that ITS-G5 communication is achieved using enough RSUs to enable full coverage of the motorway (1 RSU per segment (~500 m) placed at the beginning of each segment). For Scenarios 3 and 4, i.e. using Mode 2 for the controller, and for the highest penetration rate (30-45-25) we run the ten replications again assuming mid coverage of RSUs (1 RSU per 4 segments (~2km)) and low coverage of RSUs (1 RSU per 10 segments (~5km)). This will add a small delay in the application of the control decisions, but as the frequescy of control changes requested per segment is low, it is expected that the detioration of the efficiency improvement will be very small. Indeed, for Scenario 3 the weighted mean delay over all replications improves by 42.5% over the no-control case when full RSU coverage is used, while the improvement is 40.8% and 40.2% when mid and low RSU coverage is used, respectively. For Scenario 4 the weighted mean delay over all replications improves by 53.5% over the no-control case when full RSU coverage is used, while the improvement is 53.0% and 50.6% when mid and low RSU coverage is used, respectively. As a result, we can conclude that there is no need for full coverage of the motorway with RSUs and that even with a cost that is 10% compared to the case of full coverage the controller is abe to achive significant improvements.

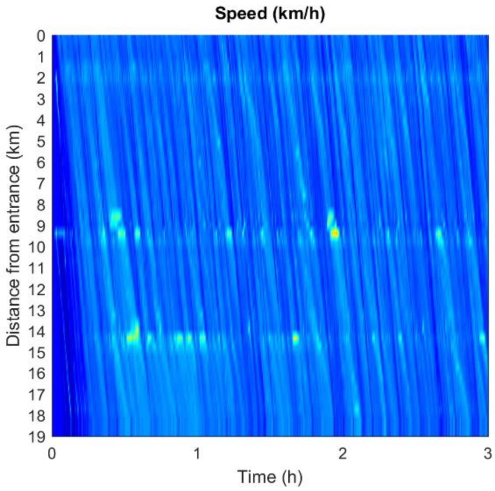
A simple but effective ACC-based control strategy has been applied in this section. The strategy aims to adjust in real time the ACC settings of equipped and connected vehicles based on the prevailing traffic conditions. It achieves great results especially when low time-gaps are suggested ($T_{min} = 0.8$ s) while it achieves very good results even when the time-gaps suggested are a bit higher ($T_{min} = 1.0$ s) and comparable the values used by manually driven vehicles.



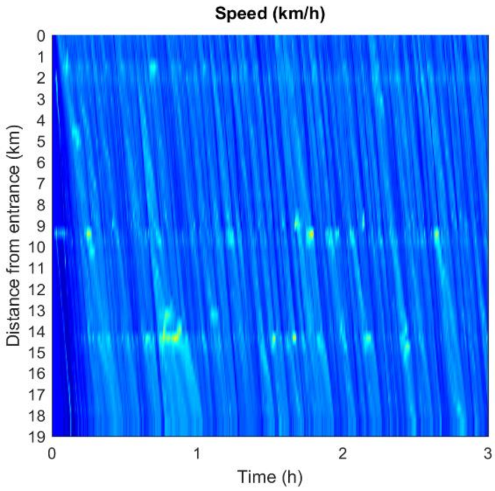
94-2-2



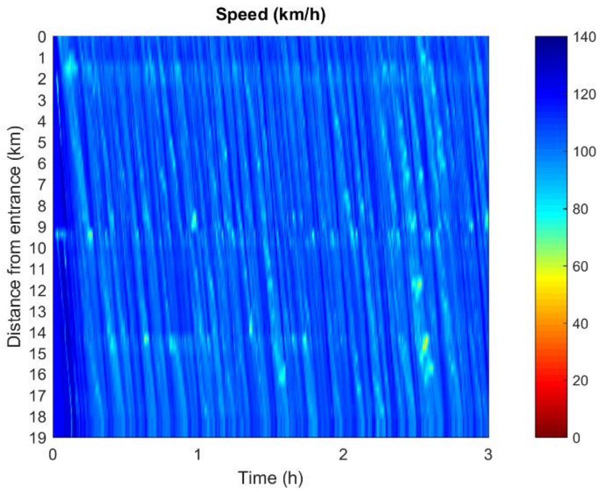
85-10-5



70-20-10



55-30-15



30-45-25

Figure 44. Spatio-temporal diagrams of speed considering various penetration rates for Scenario 3

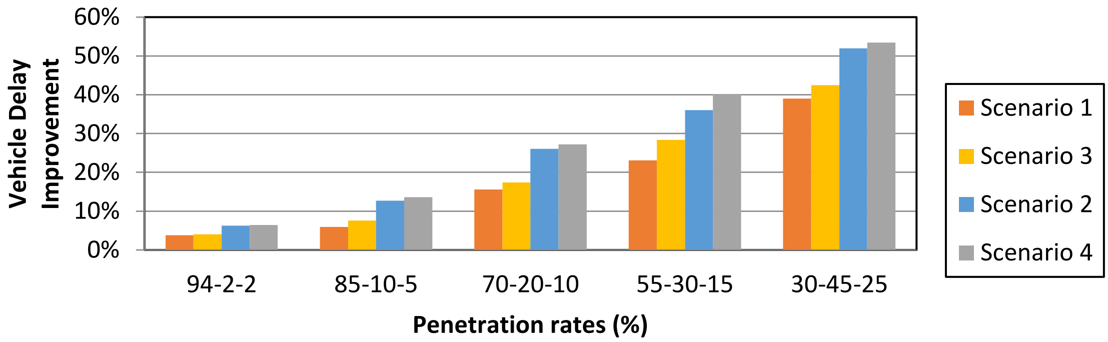


Figure 45. Vehicle delay improvement bar chart for all scenarios

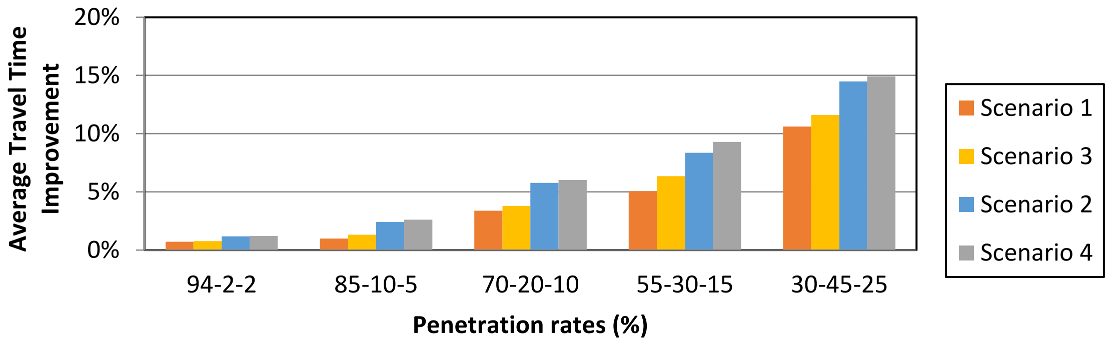


Figure 46. Average travel time improvement bar chart for all scenarios

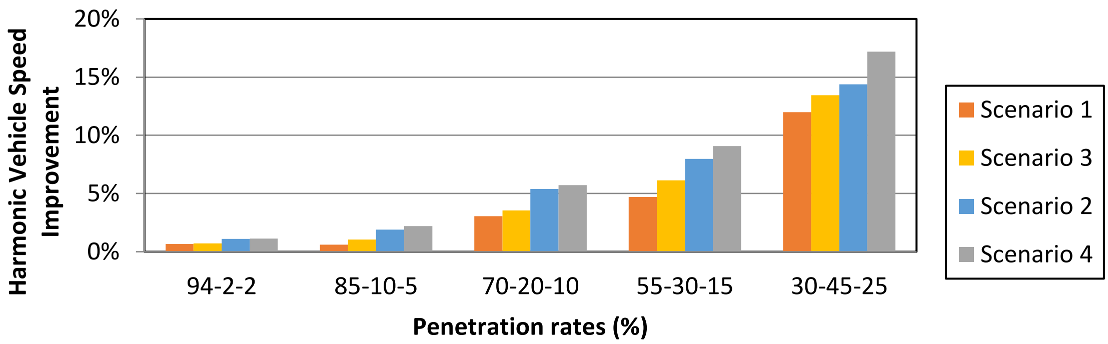


Figure 47. Harmonic vehicle speed improvement bar chart for all scenarios

7.2.2. Lane Change Advice

Bottleneck locations can be motorway merge areas, areas with a particular infrastructure layout (such as lane drops, strong grade or curvature, tunnels or bridges etc.), areas with specific traffic conditions (e.g. strong weaving of traffic streams) or areas with external capacity-reducing events (e.g. work-zones, incidents). If the arriving demand is higher than the bottleneck capacity, the bottleneck is activated, i.e. congestion is formed upstream of the bottleneck location. It should be emphasised, however, that, according to empirical investigations [19], capacity flow in conventional traffic is not reached simultaneously at all lanes. The findings of the latter investigations are in agreement with findings of the TUC group that developed the controller discussed in this section. Thus, traffic breakdown may occur on one lane, while capacity reserves are still available on other lanes. This implies that the potentially achievable cross-lane capacity is not fully exploited. Naturally, once congestion appears on one lane, it spreads fast to the other lanes as well, as drivers on the affected lane attempt to escape the speed drop via lane changing. After congestion has occurred, retarded and different vehicle acceleration at the congestion head causes the so-called capacity drop phenomenon, which breeds a reduction in the mainstream flow of a motorway, while congestion is forming upstream of the bottleneck location.

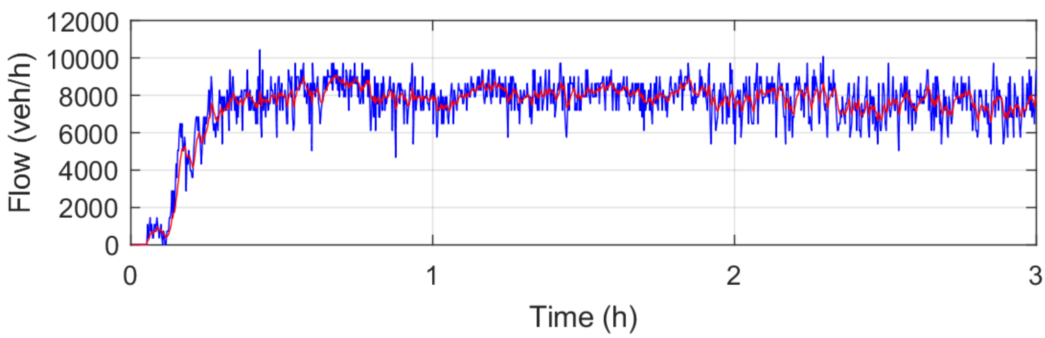
Lane-change control (LCC) is a promising new strategy [20], [21] that can be exploited for traffic management providing lane-change advice (LCA). The basic goal of LCC is to achieve a desired distribution of vehicles among the lanes in the immediate proximity of a bottleneck location e.g. motorway merge areas, areas with a particular infrastructure layout (such as lane drops, strong grade or curvature, tunnels or bridges etc.), so as to exploit the capacity of each and every lane, thus increasing the overall (cross-lane) capacity. To this end, a linear state feedback-feedforward control law, resulting from an appropriate linear-quadratic regulator problem formulation, has been is developed and is presented in Deliverable 2.5. The considered system under control comprises a number of interacting segment-lanes upstream of the bottleneck; while the feedback control law computes adequate lateral (lane-changing) flows for each segment-lane to be implemented by equipped vehicles, thus enabling an opportune, pre-specified distribution of traffic flow among the lanes. More specifically, the feedback control law uses real-time measurements of the state of the system, i.e. of all segment-lane densities, as well as of the external demand and is targeting appropriate pre-specified set-points of lane-based traffic densities.

The LCC law delivers every 10 sec "macroscopic" lateral flows that have to be applied within the next control step in order to achieve the optimal result. These lateral flows correspond to the number of vehicles moving from lane j to lane $j+1$ when positive, or the number of vehicles moving from lane $j+1$ to lane j when negative. For application to a microscopic simulation environment, these lateral flows are translated to lane change advices (to the left and to the right) to be communicated within the following control step to an appropriate number of connected vehicles (CCVs or AVs) in each segment-lane that are used as actuators for these decisions. For low penetration rates of connected vehicles it may be necessary to use all equipped vehicles within a segment-lane, while in high penetration rates it may be enough to use only some of them. Lane changing movements by the non-equipped vehicles are considered to be a disturbance for the controller, which is however rejected thanks to the feedback nature of the regulator used.

A software tool has been developed within WP2 that implements the control strategy in a generic way, while some preliminary results are presented in Deliverable 2.5 using a model in AIMSUN. The strategy has now been evaluated using the co-simulation environment for the Spanish test site utilizing a realistic demand profile for the mainstream and a synthetic demand for the most downstream on-ramp. The full population of vehicles includes the following groups: (slow/fast) cars (vehicles), trailers and motorcycles. The user is able to easily modify the penetration rate for CVs (conventional vehicles), CCVs (connected conventional vehicles) and AVs (automated vehicles) among all vehicles. AVs apply the suggested advices immediately while CCVs apply them with a delay. Of course, lane change advices are applied only if this is possible considering all other safety related checks performed by the simulator. All configuration parameters for the controller are given by the user through an input file.

Apart from the no-control scenario presented already in section 7.2.1, a control scenario has been defined for every penetration rate considered. Ten replications are conducted for each scenario and for each penetration rate for a simulation horizon of 3 hours. Each replication has the same average demand profile and the same mean values for all vehicle-related parameters. Unfortunately, these investigations were not successful in improving efficiency. We have tried dozens of different set-points per lane at the area of the bottleneck, i.e. the merge area of the third on-ramp (segment 30), and we finally concluded that when congestion is activated at this area, i.e. at segment-lane 30-1, capacity flow has already been reached quasi-simultaneously at all lanes. As a result, there are no capacity reserves to be exploited by the controller.

Figure 48 presents aggregated flow, average density and average speed trajectories at segment 30 for a specific replication with a penetration rate for CV-CCV-AV equal to 30-45-25. Congestion is activated about 50 min after the start of the simulation (see the related speed drop and density increase) and leads to a capacity drop that is reducing the throughput of the system. If we now look at the flow trajectories per lane for the same segment (see *Figure 49*) we can conclude that lanes 3 and 4 are carrying very high flows, reaching values of some 2300 veh/h and 2500 veh/h, respectively, well in advance of the congestion onset. At the same time, lanes 1 and 2 are carrying lower values of flow, that are, however, around capacity as these lanes are mostly utilised by trailers which are quite longer compared to cars and, as a result, occupy considerably more space. The distribution of flows per lane is the same for all replications considered and is, unfortunately, not in agreement with observations of real data in many different motorways around the world. At this point, we should note that if we try to use higher density set points per lane in an attempt to get even more flow being served on the fast lanes, then congestion is first activated there. As a result, we can conclude that there are no capacity reserves at the fast lanes and that the LCC controller is not able exploit any such possibility. In the following section we will discuss why the distribution of flows per lane is similar even for the case of mainstream traffic flow control leading to similar difficulties when trying to combine the use of VSL actions with LCC.



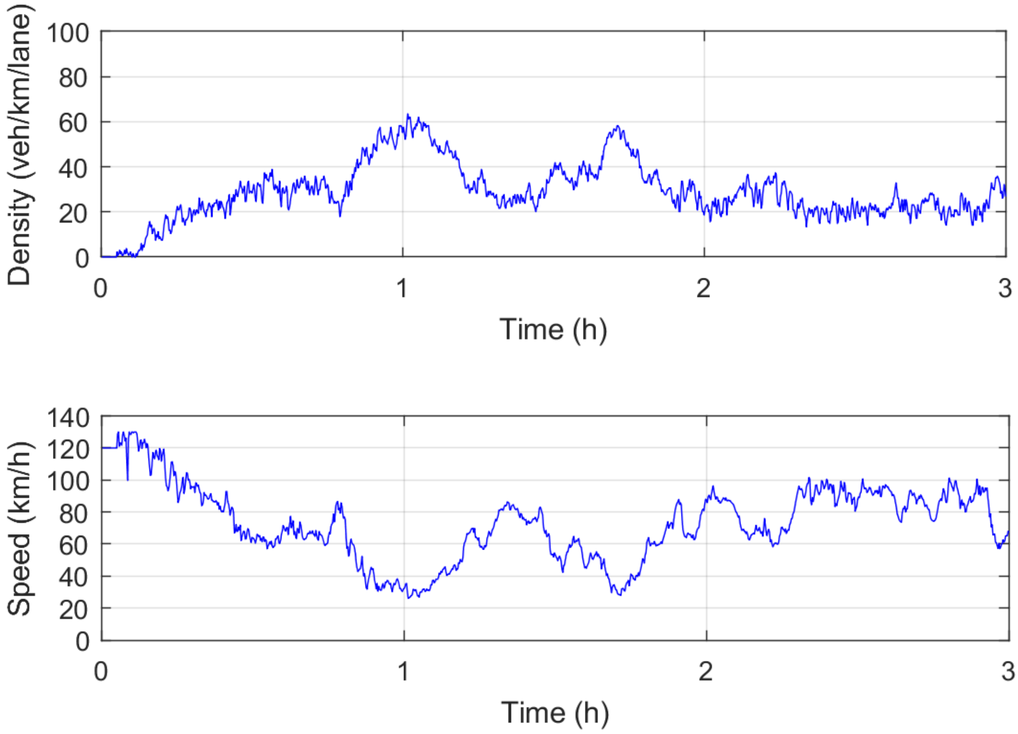
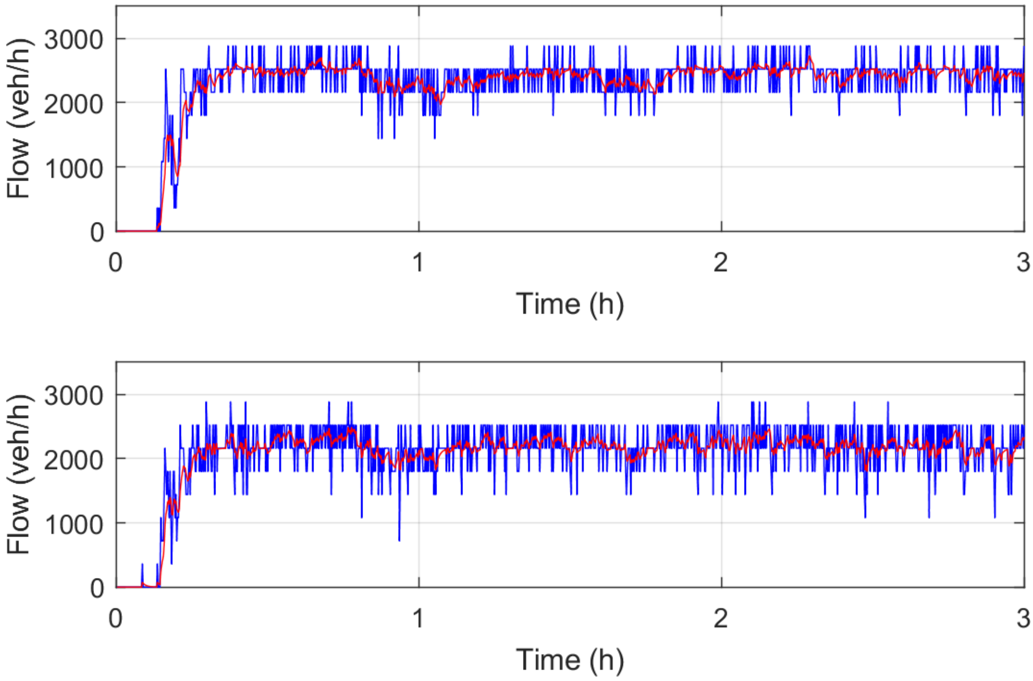


Figure 48. Flow (smoothed flow), density and speed trajectories at segment 30 for the no-control scenario with a penetration rate (30-45-25)



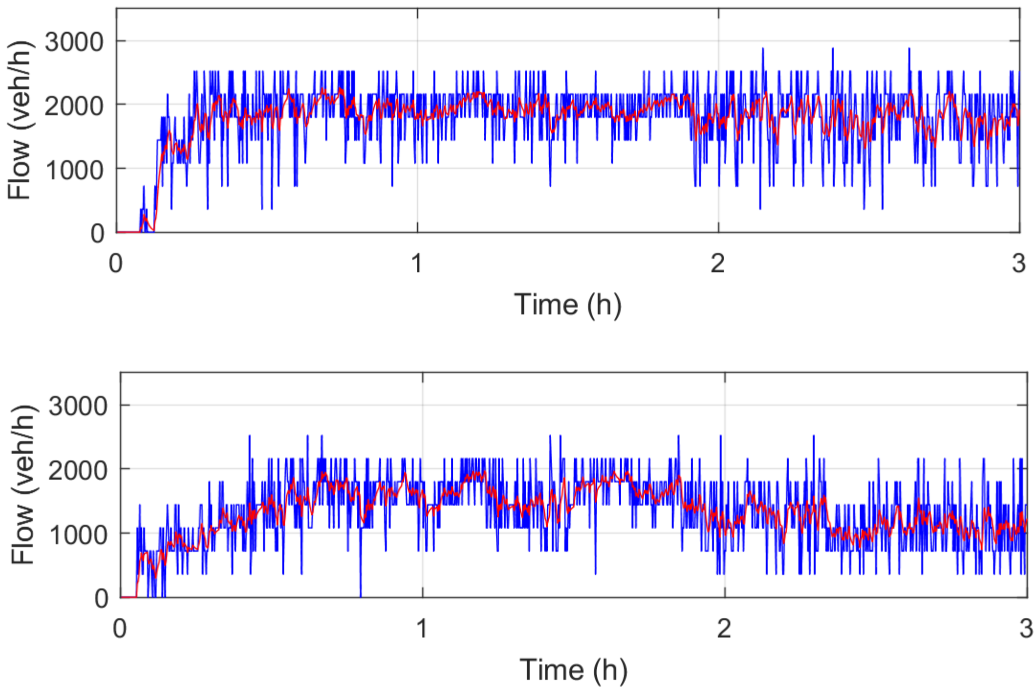


Figure 49. Flow (smoothed flow) trajectories at segment 30 and lanes 1 (bottom) to 4 (top) for the no-control scenario with a penetration rate (30-45-25)

7.2.3 Mainstream traffic flow control

Variable speed limits (VSLs) displayed on roadside or overhead variable message signs (VMSs) in response to prevailing traffic conditions is an increasingly popular motorway traffic control measure. Till recently, the main targeted impact of VSLs was enhanced traffic safety as a result of the homogenisation of speeds of individual vehicles and of the mean speeds of different motorway lanes which reduce the accident risk. In [15], it was shown that VSL can be used in order to create a temporal or even a permanent flow decrease and, as a result, they can be used by a control strategy in order to regulate the outflow of a motorway area.

The main purpose of mainstream traffic flow control (MTFC) is to enable the mainstream traffic flow that is approaching areas with particular infrastructure layout, e.g. on-ramp merges, mainstream lane-drops or other bottlenecks, to take values that will allow the establishment of optimal traffic conditions for any appearing demand [16], [17]. This can be achieved using VSLs as actuators and a control strategy that maintains the density at the bottleneck area around a set-point that can be set equal to the critical density, i.e. the density that corresponds to the capacity of the bottleneck.

MTFC actions are employed at an area upstream of the *bottleneck* location, leaving enough space for the vehicles to accelerate within the *acceleration area* and reach the bottleneck with increased speed avoiding (or delaying) congestion activation and the related capacity drop phenomenon; thus higher outflow is achieved (see *Figure 50*). Of course a controlled congestion is formed at the *MTFC application area* that spills back further upstream. Appropriate VSLs can be applied there (*Safety area*) in order to ensure a smooth reduction of speed and a safer vehicle approach to the MTFC application area. This controlled congestion is significantly reduced in space and time compared to the congestion created in the no-control case and has higher internal speeds due to the increased outflow (capacity) values. This also leads to less blocking of off-ramps and hence further improvements on the motorway.

VSLs can be displayed on appropriately located VMSs and/or can be communicated to connected vehicles according to their current location on the motorway. Such a VSL message can be used either as on-board information to be applied manually by the driver or as an order to be applied automatically by AVs. It is expected that, for a sufficient penetration of equipped vehicles, this will be sufficient to impose the speed limit to non-equipped vehicles as well; hence, no VMSs would be necessary. Nevertheless, the use of VMSs is suggested in order to properly inform the drivers of vehicles that are not connected.

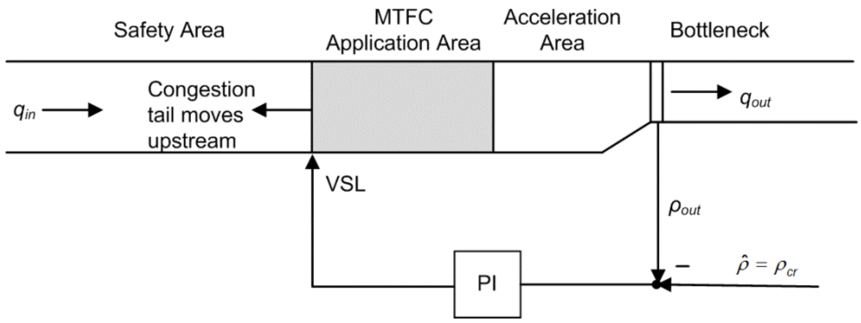


Figure 50. The MTFC concept

A Proportional-Integral (PI) feedback regulator, presented in Deliverable 2.5, is employed for MTFC, keeping the bottleneck density ρ close to the selected set-point $\hat{\rho}$ using real time measurements of ρ [18]. The set-point is typically selected around the critical density value, at which capacity flow is achieved at the bottleneck location. The time period T for updating decisions is set equal to 60 s. The $vsl(k)$ value delivered by the control strategy at time k is truncated to remain within a range of admissible VSL values $[60,130]$ km/h. As discussed above, the VSL value is displayed at a VMS located at the beginning of the MTFC application area/segment and/or is sent for application to all connected vehicles that are located in the same area/segment. Upstream of the MTFC application area there is a VSL safety area (divided into one or more subareas/segments) where speed limits are also applied (gradually increasing from a segment to the upstream one) to ensure a smooth reduction of speed and a safer vehicle approach to the MTFC application area. Furthermore, downstream of the MTFC application area, an acceleration area follows where an increased VSL is employed in order to allow a quick recovery of higher speeds by the vehicles so as to avoid the capacity drop and maximize the bottleneck throughput.

Some VSL practical implementation aspects are taken into account. The VSL obtained from the regulator is rounded before its application to the closest value of a set of predefined discrete values (130, 120, 110, 100, 90, 80, 70, 60 km/h). Furthermore, the difference between two consecutive VSL values received by VMSs and/or connected vehicles in an area of the motorway is limited (e.g. to ± 20 km/h), so as to avoid abrupt speed changes. Also, the difference between two VSL values at consecutive areas/segments at the same control period is limited (e.g. to 20 km/h), as often required in practice, in order to achieve a safe approach of vehicles within the safety area.

A software tool has been developed within WP2 that implements the control strategy in a generic way. The strategy has now been evaluated using the co-simulation environment for the Spanish test site utilizing a realistic demand profile for the mainstream and a synthetic demand for the most downstream on-ramp.

At this point we need to note that the use of VSL within a range of values $[60,130]$ km/h leads only to temporal flow (outflow of the MTFC area) reduction in order to hold back some vehicles and avoid congestion at the bottleneck. The temporal flow reduction leads to density increase at the MTFC area. If we observe the data per lane for the MTFC area, we can conclude that the temporal flow reduction is stronger for the slow lanes compared to the fast ones. Also, the microscopic SUMO model used by the co-simulation environment has the tendency to perform lane changes towards the fast lane, especially within the acceleration area (segment 29 at the current setting) and the bottleneck area (segment 30). This is possibly due to the parameters used after the necessary calibration of the model for the realization of the capacity drop phenomena. These lane changes towards the fast lanes have as a result high flow values for the fast lanes at the merge area and no capacity reserve to be exploited by the LCC strategy.

7.2.3.1 Analysis of Infrastructure requirements for Variable Speed Limit Control

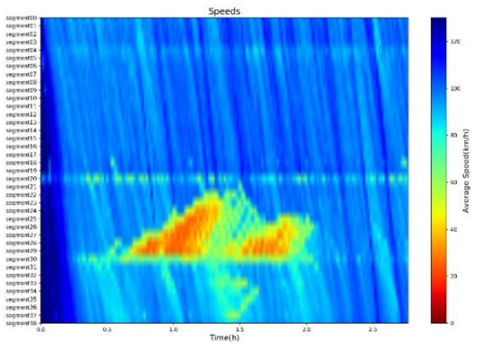
The MTFC strategy requires that vehicles receive information on speed limits which are variable and change dynamically according to the decisions of the controller. This information can reach the vehicles in two ways: first, variable message signs are placed along the highway with a sufficient coverage, or second, the vehicles receive speed limit/speed advice information via V2X messages, e.g. IVIM. While the latter is a more advanced technique for future implementations, the former is already implemented on most of the highways. The main question here is, how many variable speed limits need to be placed along the highway so that the controller still works in a sufficient way. In this analysis, two configurations will be virtually tested with the AP7 Girona scenario and compared with each other:

1. **For each segment** of the test site, one VMS is placed at its entry. This very dense configuration allows to address the vehicles very early as soon as the controller changes a speed limit. Therefore, this configuration is expected to have the maximum effect on efficiency. This configuration is called “**Full VMS**” in upcoming figures and tables.
2. Only **for few segments** a VMS is placed at the segments entry. Those segments have been chooen wisely according to the needs of the controller. For each on-ramp, five VMS are required: one for the merge area of the on-ramp, one for the actual control area which is placed about 1 km upstream, and another three VMS for implementing safety areas which reduce the speed limit slowly one after another towards the actual speed limit in the control area, in order to avoid unsafe braking maneuvers. In total, five VMS are placed between two on-ramps along the test site following this scheme. This configuration is called “**Few VMS**” in upcoming figures and tables.

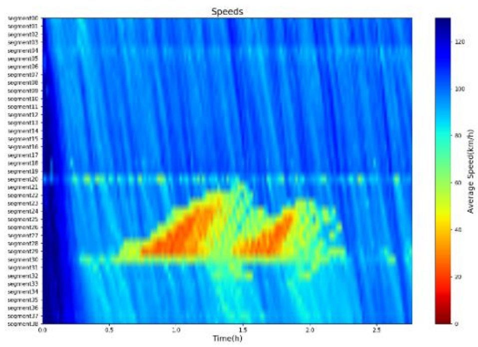
In addition to the actual speed signs, which are used to reach conventional vehicles in order to control their speed, connected conventional vehicles and automated vehicles receive the control decisions via IVI messages as speed advices. Those vehicles react according to the sent advices as proposed in D2.3. Automated vehicles treat speed advices as speed limist and will follow them once received. Connected conventional vehicles can react on the speed advices as well, but can also miss or ignore received advices. Furthermore, they have a certain delay before they react on speed advices. The complete model is decribed in Deliverable D2.3.

7.2.3.2 No-control cases as baseline for the analysis

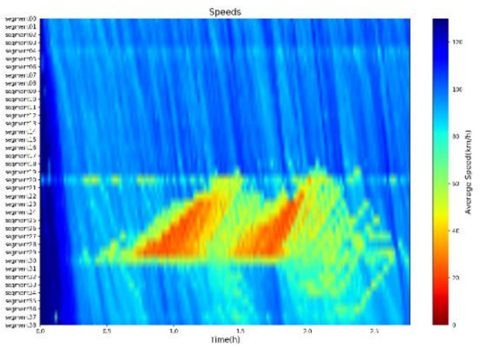
Next to the presented VMS configurations, a no control case is simulated having only static speed signs and no control decisions at all. For four different penetration rates (0%, 5%, 10%, 25% AVs) different on-ramp traffic is configured. This decision has been made in order to compare only the situations in which the VSL controller works best. By reducing the amount of additional on-ramp traffic with higher penetration rates of AVs, the level of congestion is kept almost the same throughout this specific analysis. The following speed contour plots in Figure 51 are generated for each of the penetration rate configurations in the no control case (for one specific random seed):



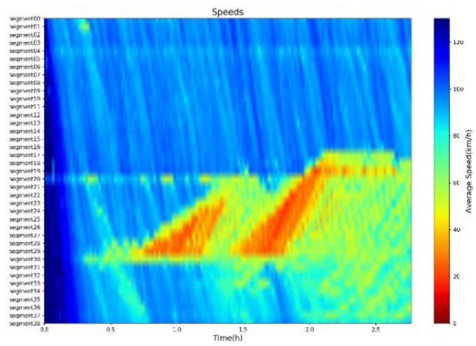
Penetration Rate: (100-0-0)
On-Ramp Traffic: 1500 veh/h



Penetration Rate: (85-10-5)
On-Ramp Traffic: 1300 veh/h



Penetration Rate: (70-20-10)
On-Ramp Traffic: 1250 veh/h



Penetration Rate: (35-45-25)
On-Ramp Traffic: 1050 veh/h

Figure 51. Speeds over time on the test site for different penetration rate configurations of the no-control case

7.2.3.3 KPI for Traffic Efficiency Improvement

In this analysis, we stick to the average travel time delay as the main KPI. The travel time delay describes the travel time a vehicle actually has compared to a free-flow situation without any other vehicles. This measure reflects the level of congestion within the system in a good way, as it does not take into account the remaining travel costs the vehicle already has. The average values of delay time (arithmetic mean over all vehicles) for the no control case are the following (averaged over all simulation replications). For completeness, the average travel time is given as well.

Penetration Rate	100-0-0	85-10-5	70-20-10	35-45-25
Mean Travel Time Delay	**227 s**	**218 s**	**287 s**	**317 s**
Mean Travel Time	750 s	748 s	818 s	854 s

Figure 52. No control case delay time and travel time

The improvement in traffic efficiency is therefore given by comparing travel time delay D of the measurement case against the no control case (baseline).

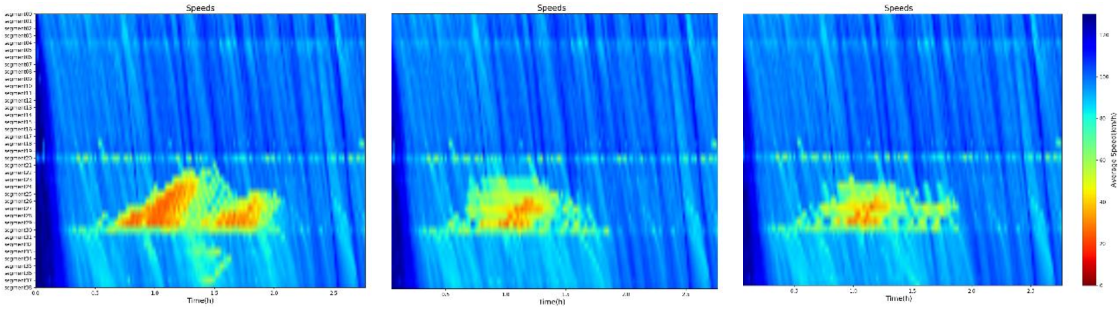
This is done straight-forward by using:

$$KPI_{Delay} = \frac{D_{measure} - D_{baseline}}{D_{baseline}}$$

Penetration rate (100 - 00 - 00)

In this first case, no vehicle is equipped with autonomous vehicle functions nor communication devices. Vehicles react on speed limits shown on variable message signs which are dynamically set by the MTF controller. It can be shown, that even in this simple configuration the controller is able to dissolve the congestion from the no-control case. The controller reacts quite early by reducing the speed limit stepwise up to 60 km/h, thereby reducing the mainstream flow. The moment of the capacity drop at the on-ramp is delayed in almost every cases, so that less congestion occurs. The second wave of additional traffic flow does not lead to a capacity drop at all due to the controllers decisions, thereby resulting in an average improvement in travel time delay of 14%. Having only few VMS along the highway results in similar results, with a little less of an improvement of 10%.

No-Control Case | **Full VMS** | **Few VMS**



	No-Control	Full VMS	Few VMS
Mean Travel Time Delay	227 s	195 s	204 s
KPI_{Delay}	-	**14.3 %**	**10.2 %**

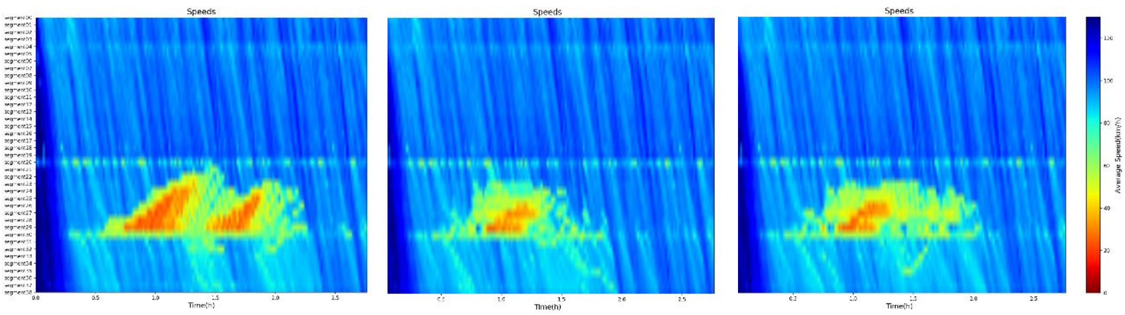
Figure 53. No-control compared to Full VMS and few VMS. Penetration rate 100-0-0

Penetration rate (85 - 10 - 05)

In this second analysis, five percent of the vehicles are using autonomous vehicle functions. In general, the maximum throughput at the bottleneck reduces due to the bigger time-gap AVs have compared to conventional vehicles . As a result, the capacity drop near the merge area is observed earlier resulting in longer congestion (both in time and space). In such cases, the controller won't be able to work as effective as it could. To compensate this problem for this penetration rate configuration, the on-ramp traffic has been reduced as shown in section 7.2.3.2.

Having five percent of autonomous vehicles and additional 10% of the vehicles connected, the improvement in traffic efficiency is similar to the first case. Using a full VMS deployment results in an improvement of 11%, while only few placed VMS reduce this improvement to 8%. However, it is shown that with a low coverage of variable message signs the controller is still able to reduce traffic congestion and improve traffic efficiency as result.

No-Control Case | **Full VMS** | **Few VMS**

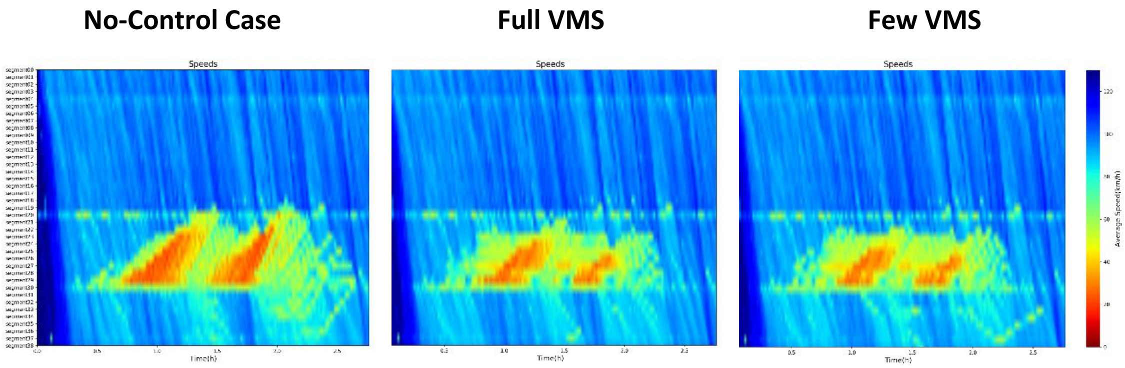


	No-Control	Full VMS	Few VMS
Mean Travel Time Delay	218 s	193 s	202 s
KPI_{Delay}	-	**11.2 %**	**7.5 %**

Figure 54. No-control compared to Full VMS and few VMS. Penetration rate 85-10-05

Penetration rate (70 - 20 - 10)

With 10% of the vehicles being automated, the no-control case already results in low travel times due to increased congestion. This case is already hard to solve for the MTF controller. The congestion can never be dissolved completely, yet there is a noticeable reduction. In this case the coverage of variable message signs already plays no important role any more, as the low coverage case results in similar improvements compared to the full coverage fo VMS. In average, both configurations result in an improvement of about 14%. It needs to be mentioned, that quite many vehicles are already connected and therefore receive control decisions via IVI messages and react on those by reducing their speed. This fact contributes to the rather good improvement even with a low coverage of VMS, as connected vehicles can react early on control decisions and influence other traffic participants by their speed adaptations.



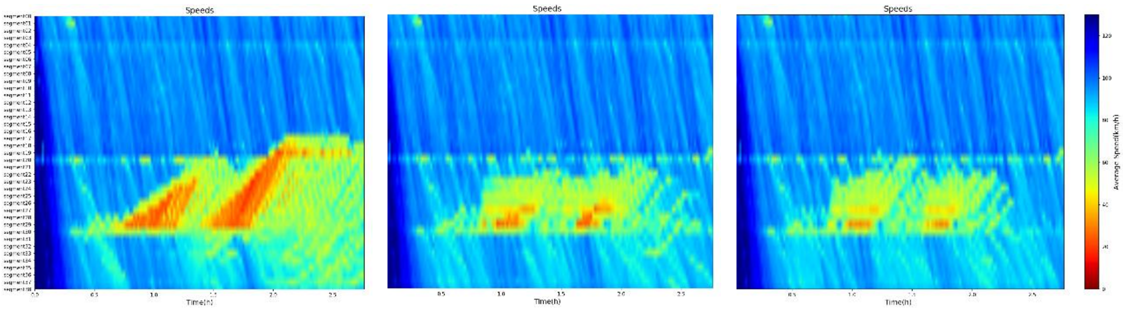
	No-Control	Full VMS	Few VMS
Mean Travel Time Delay	287 s	245 s	247 s
KPI_{Delay}	-	**14.5 %**	**14.2 %**

Figure 55. No-control compared to Full VMS and few VMS. Penetration rate 70-20-10

Penetration rate (30 - 45 - 25)

In the last case, a quarter of all vehicles uses autonomous vehicle functions. In addition, 45 percent of the vehicles are connected and receive speed advices from the controller. The no-control case already shows a rather bad situation with congestion due to the increased time gap of AVs. In most of the cases, the controller is able to partitially dissolve this congestion. Thus, the traffic efficiency can be improved again by 13% with the full coverage, and by almost 14% with the low coverage of VMS. The slight difference between both configurations is just very low and can be treated as equal performance.

No-Control Case **Full VMS** **Few VMS**

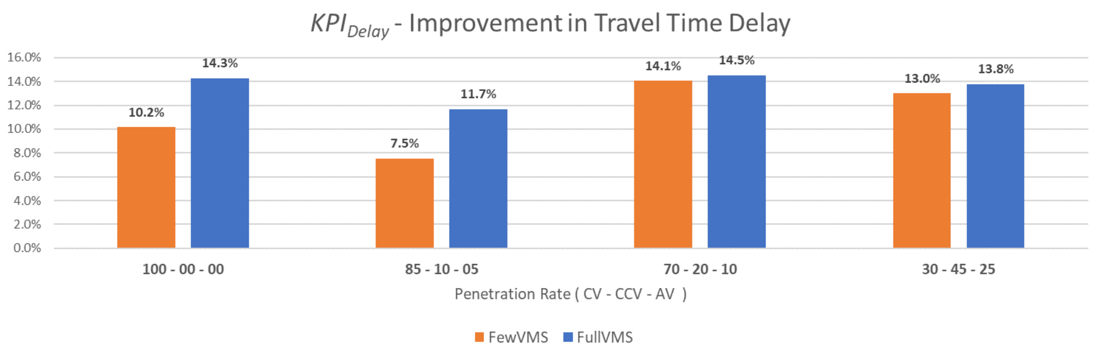


Penetration Rate	No-Control	Full VMS	Few VMS
Mean Travel Time Delay	317 s	273 s	275 s
KPI_{Delay}	**-**	**13.8 %**	**13.0 %**

Figure 56. No-control compared to Full VMS and few VMS. Penetration rate 30-45-25

7.2.3.4 Conclusion

Concluding, the MTF controller is able to dissolve congestion at bottlenecks due to exceeding capacity by reducing the speed and therefore the flow of the main stream traffic. The performance of this control strategy is not directly related to the penetration rate of the traffic. The traffic efficiency can be improved in average by up to 14 percent, independent of vehicles being equipped with communication devices. However, a reduction of variable message signs from a full deployment (every 500m) to a more strategic positioning of the VMS (e.g. five VMS per on-ramp) is feasible and leads to equal or slightly lower results in traffic efficiency improvement. In such cases, traffic efficiency can still be improved by 10 percent using the MTF controller. In addition to a lower coverage of VMS, communication of speed advices via IVI message to the vehicles have positive effects for higher penetration rates.



Penetration Rate	No-Control	Full Vms	Few Vms
100 - 00 - 00	227 s	195 s **(14.3%)**	204 s **(10.2%)**
85 - 10 - 05	218 s	193 s **(11.2%)**	202 s **(7.5%)**
70 - 20 - 10	287 s	245 s **(14.5%)**	247 s **(14.2%)**
30 - 45 - 25	317 s	273 s **(13.8%)**	275 **(13.0%)**

Figure 57. No-control compared to Full VMS and few VMS. Aggregated results

7.2.4 Beyond physical infrastructure – Using communication only to control traffic

In addition to controlling the traffic by setting variable message signs, vehicles do receive speed limits or speed advices via communication using IVI messages. Those messages contain control decisions for each segment lanes and are spread to the vehicles using ITS-G5 adhoc communication. For this purpose, the simulation scenario is modelled in a way, that a road side unit is placed at each segment entry. Each road side unit broadcasts the IVI messages to vehicles in its range. Equipped vehicles adjust their speeds and therefore control the traffic flow as a whole, as other vehicles (e.g. their leaders) are forced to adjust their speeds as well.

With this fact given, we propose the hypothesis, that *variable message signs are not required if the equipment rate of connected and automated vehicles reach a certain amount*.

7.2.4.1 Results

In order to examine the stated hypothesis, we executed additional simulation series, where control decisions in form of speed limits are spread via the communication link only. In this analysis, conventional vehicles follow static speed signs only which display a fixed speed of 130 km/h. Connected conventional vehicles and automated vehicles follow speed limits as described in D2.3 based on IVI messages. With the same penetration rates as in the previous study, the following results were obtained:

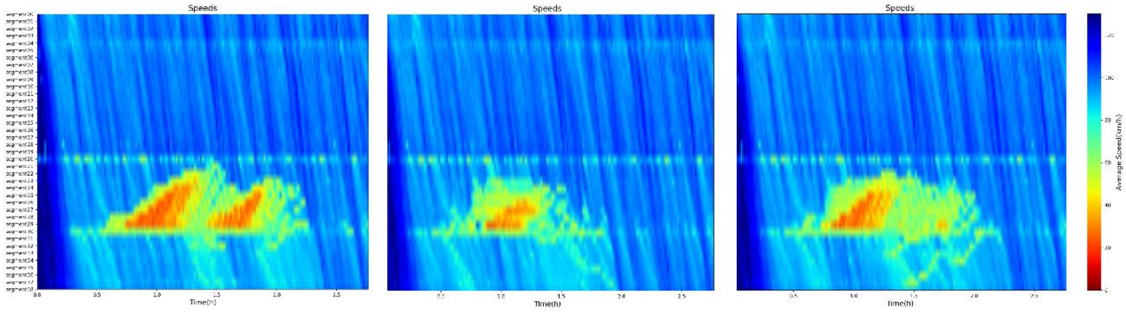
Penetration rate (100 - 00 - 00)

As expected, with a penetration rate of zero percent connected vehicles, the simulation outcome is exactly the same as without any controller active.

Penetration rate (85 - 10 - 05)

Having a penetration rate of five percent of automated vehicles, and ten percent of connected vehicles which follow the advices most of the time, but also ignore advices, the traffic efficiency could be improved by 8%, compared to 12% if every segment would be equipped with a VMS.

No-Control Case | **Full VMS** | **Communication Only**



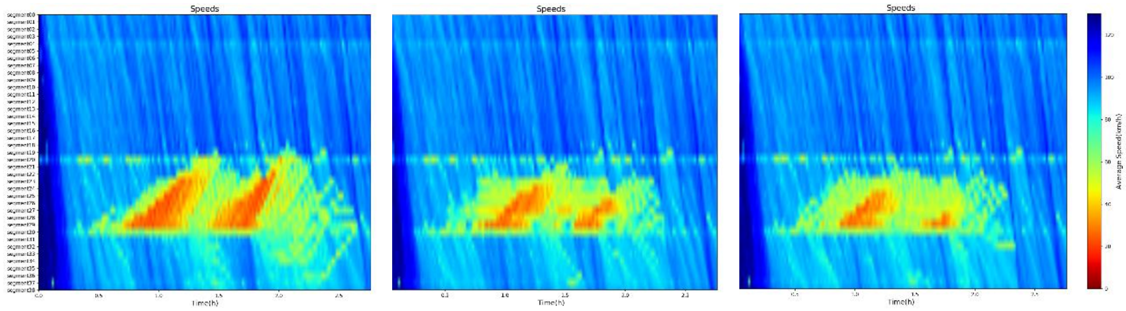
	No-Control	Full VMS	Communication Only
Mean Travel Time Delay	218 s	193 s	200 s
KPI_{Delay}	-	11.2 %	**8.4 %**

Figure 58. No-control compared to Full VMS and Communication only. Penetration rate 85-10-05

Penetration rate (70 - 20 - 10)

For higher penetration rates the traffic efficieny can be improved by an equal amount as having VMS deployed along the highway. In average, only slight differences could be observed. The amount of vehicles which react on received speed advices is enough, so that other traffic participants are affected by the control decisions. The overall traffic slows down and, therefore, reduces the main stream flow at the bottleneck section.

No-Control Case | **Full VMS** | **Communication Only**



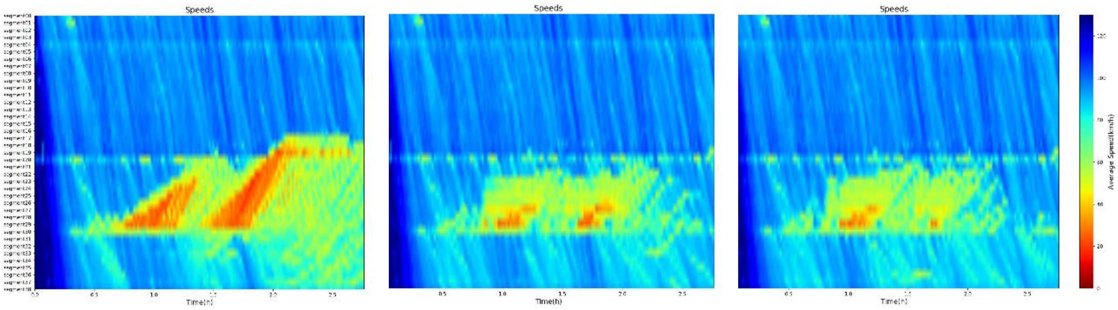
	No-Control	Full VMS	Communication Only
Mean Travel Time Delay	287 s	245 s	252 s
KPI_{Delay}	-	14.5 %	**12.3 %**

Figure 59. No-control compared to Full VMS and Communication only. Penetration rate 70-20-10

Penetration rate (30 - 45 - 25)

If the majority of vehicles is connected, the improvement is only slightly better. No remarkable difference could be observed, when comparing traffic control via VMS or communication only.

No-Control Case | **Full VMS** | **Communication Only**

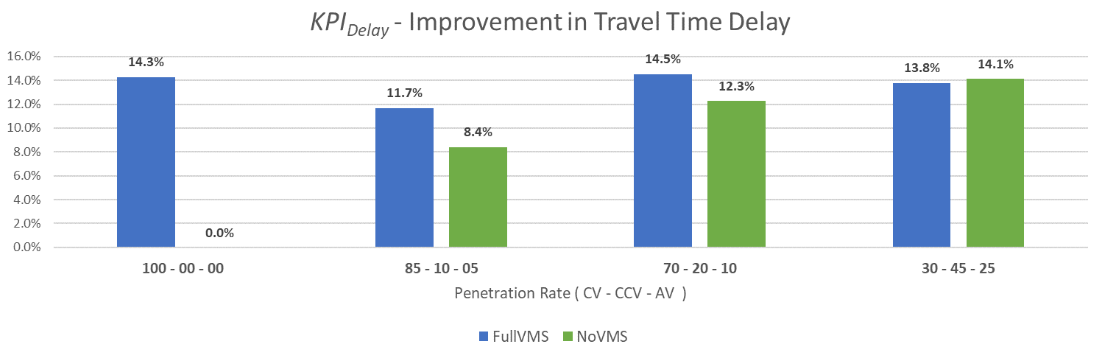


Penetration Rate	No-Control	Full VMS	Communication Only
Mean Travel Time Delay	317 s	273 s	275 s
KPI_{Delay}	-	13.8 %	**13.1 %**

Figure 60. No-control compared to Full VMS and Communication only. Penetration rate 30-45-25

7.2.4.2 Conclusion

Concluding, our hypothesis could be emphasized by the performed simulations. Variable message signs are not necessarily required to be deployed, as long as enough vehicles are equipped with communication devices to follow speed advices. In this analysis, a 30% chance of ignoring speed advices is implemented for drivers of connected conventional vehicles. Due to the dense traffic situation, in which the MTF controller gets active, only a small portion of vehicles which follow the speed advices is required in order to have effects on the main traffic flow. As a result, the traffic can be controlled by "using" only this small amount of vehicles. Eventually, even for low penetration rates, the traffic efficiency can be improved by over 8%, whereas a fully deployed VMS infrastructure would reach 12% of improvement. With higher penetration rates, the difference between using physical infrastructure or communicating advices to the vehicles is negliable. Both control implementations are equally good providing a traffic efficiency improvement of 14%.



Penetration Rate	No-Control	No VMS / I2V Control	KPI_{Delay}
100 - 00 - 00	227 s	227 s	**0 %**
85 - 10 - 05	218 s	200 s	**8.4 %**
70 - 20 - 10	287 s	252 s	**12.3 %**
30 - 45 - 25	317 s	275 s	**13.1 %**

Figure 61. No-control compared to Full VMS and Communication only. Aggregated results

7.2.5. Analysis of Communication Requirements for Variable Speed Limit Control

In the previous study, communication is used to send speed limits and speed advices to the connected vehicles. We assumed, that infrastructure for communication is implemented in a way, that each connected vehicle receives advices almost in real time and without any information loss. This assumption, however, is only true, if the infrastructure along the highway is built in a way to support this. This means for ITS-G5 communication, that enough road side units are placed along the highway in close distance to each other to enable full communication coverage. In this study, we play around with this very parameter in order to see how much communication infrastructure (i.e. number of RSUs per km) is really required in order to reach enough vehicles with IVI messages. We study four different setting:

1. **High coverage of RSUs**:

   40 RSUs are placed in 500 m equal distance (one per segment)

2. **Mid coverage of RSUs:**

   10 RSUs are placed in 2 km equal distance (one every fourth segment)

3. **Low coverage of RSUs:**

   Only 5 RSUs are placed in 4 km equal distance (one every eigth segment)

4. **Cellular Communication / No RSUs:**

   Instead of ITS-G5, the cellular link is used to send IVI messages to vehicles individualy, e.g. via LTE. This allows to use existing infrastructure so that no RSUs need to be placed along the highway. Since vehicles are usually connected to some sort of OEM cloud service (while RSUs can be connected to the IMC directly), a certain delay is assumed when sending messages via the cellular link. In this setup, a delay of 1 second is applied for both, uplink (sending CAMs from the vehicles to the IMC), and downlink communication (sending IVIMs with advices to the vehicles).

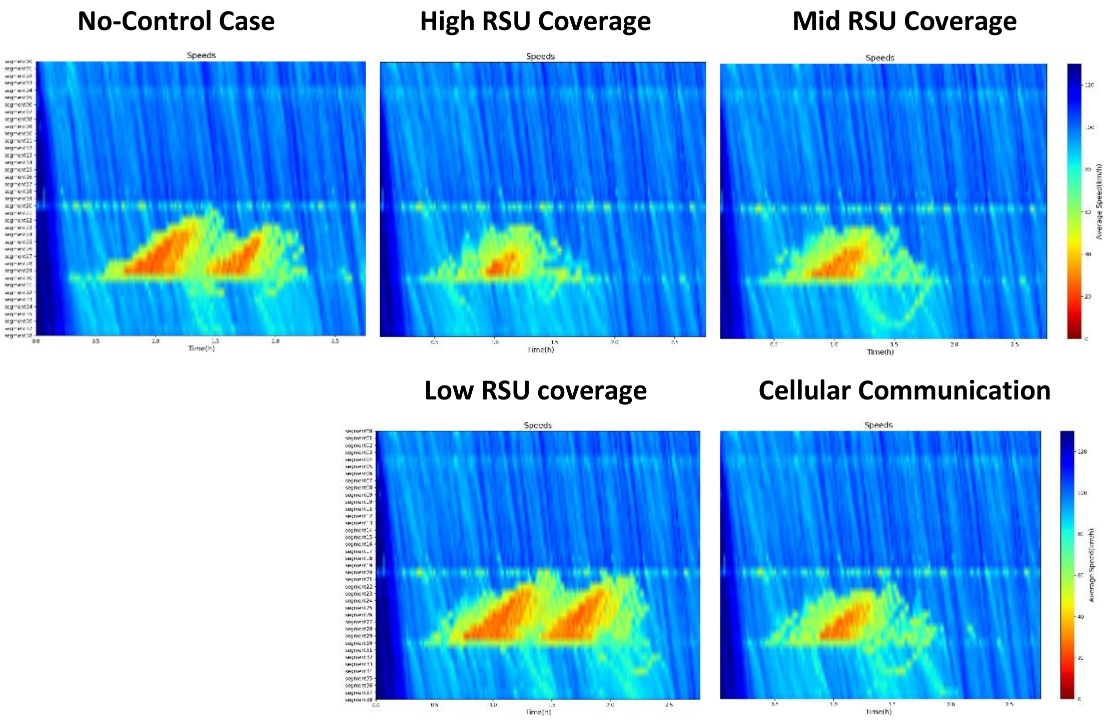
7.2.5.1 Results

Again, in this study the three penetration rate variations are tested (85-10-05, 70-20-10, 30-45-25). The case (100-0-0) is skipped as connected vehicles are required in order to see any effect of the controller. Each penetration rate variation and coverage setting is run with 10 different seeds, resulting in 120 additional simulations. The results are again compared with the no-control cases from section 7.2.2.

Penetration rate (85 - 10 - 05)

In the case of a low penetration rate, the highest improvement in traffic efficiency of 8% is achieved by implementing road side units with a high coverage of two RSUs per km. All other configurations show a lower performance of 5% improvement. This is not suprising, as messages do not always reach vehicles due to the lower RSU coverage. As a result, vehicles do not receive advices on time, or still have old advices stored which are not valid anymore and therefore initiate unwanted reactions. However, the MTF controller is still able to improve the most of the situations where no traffic control is applied.

Furthermore, it is hard to exlain why the cellular case does achieve a rather low improvement of only 5% compared to the fully covered ITS-G5 case. One important factor could be the communication delay between vehicles and IMC, as the vehicles are not directly connected with the IMC.



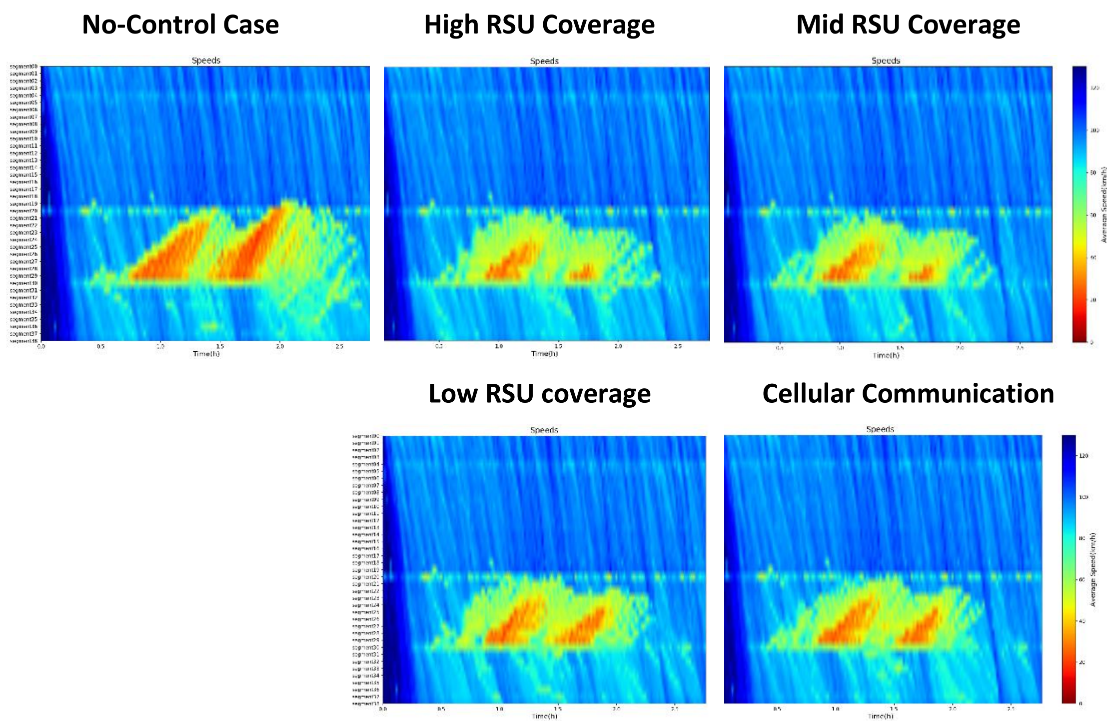
	No-Control	High RSU Coverage	Mid RSU Coverage	Low RSU Coverage	Cellular Communication
Mean Travel Time Delay	218 s	200 s	206 s	207 s	206 s
KPI_{Delay}	**-**	**8.4 %**	**5.6 %**	**5.4 %**	**5.6 %**

Figure 62. No-control compared to different RSUs coverage. Penetration rate 85-10-05

Penetration rate (70 - 20 - 10)

With a higher penetration rate of 10% AVs and 20% CCVs, the improvement again decreases with lower RSU coverage. While a full RSU coverage is able to produce an improvement of

12% in average, a low coverage of RSUs results in only 9% of improvement. In this case, the communication of advices via the cellular link achives an even better performance of 13% of improvement in average. However, there are still cases where cellular communication does not work as good as sending advices via ITS-G5 communication, as shown in the specific simulation series for one random seed below.



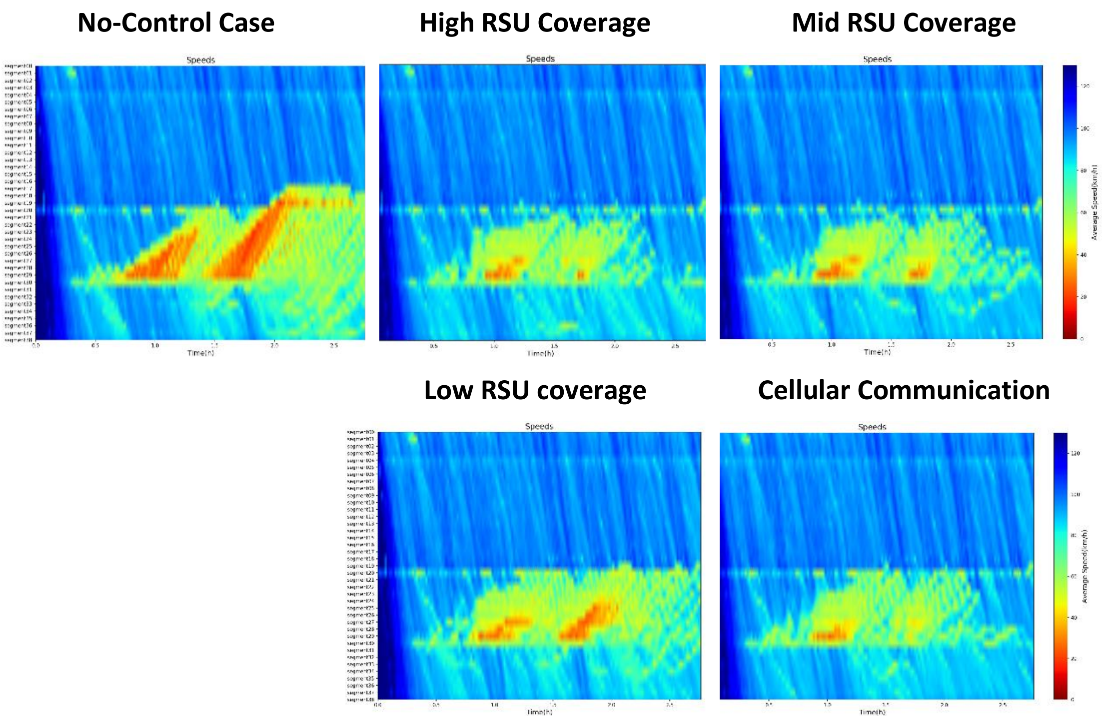
	No-Control	High RSU Coverage	Mid RSU Coverage	Low RSU Coverage	Cellular Communication
Mean Travel Time Delay	287 s	252 s	255 s	262 s	249 s
KPI_{Delay}	-	**12.3 %**	**11.1 %**	**8.8 %**	**13.2 %**

Figure 63. No-control compared to different RSUs coverage. Penetration rate 70-20-10

Penetration rate (30 - 45 - 25)

Due to the higher penetration rate of automated vehicles with higher time-gaps, the traffic gets generally more dense, which offers a good base for improvement. Additionally, due to a high amount of connected vehicles, the MTF controller works pretty well even without any VMS installed by sending IVI messages only. Having a high or mid coverage of RSUs along the highway results in similar results of 14% in improvement. However, with a low coverage the controller is not able to produce good results anymore. In some cases, the congestion is even worse than in the no-control case, presumably due to outdated advice information carried by the vehicles. As a result, the controller is not able to show positive effects in average.

In this setting, the cellular communication is also able to produce very good results of about 14% in improvement, similar to ITS-G5 with high coverage.

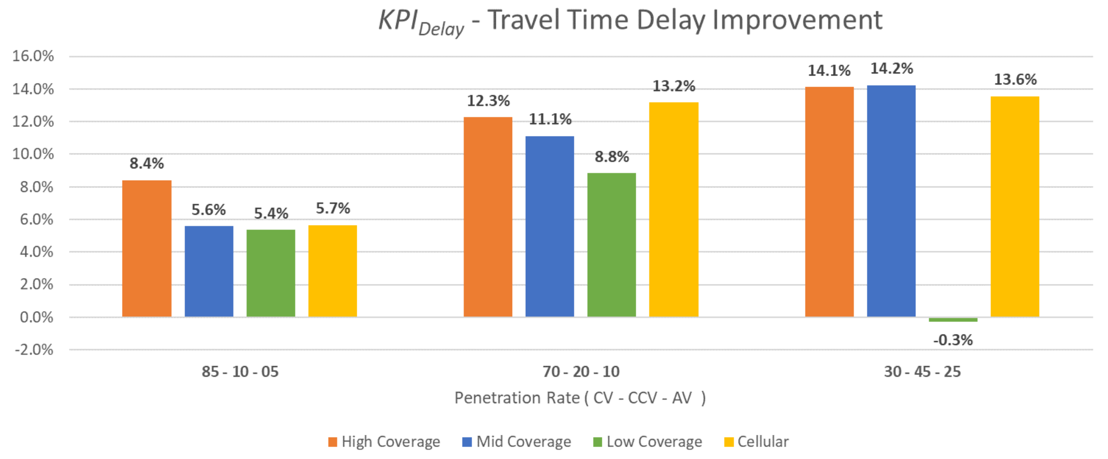


	No-Control	High RSU Coverage	Mid RSU Coverage	Low RSU Coverage	Cellular Communication
Mean Travel Time Delay	317 s	272 s	272 s	318 s	274 s
KPI_{Delay}	-	**14.1 %**	**14.2 %**	**-0.3 %**	**13.6 %**

Figure 64. No-control compared to different RSUs coverage. Penetration rate 30-45-25

7.2.5.2 Conclusion

It has been shown, that the coverage of road side units has great influence on the performance of the MTF controller. While a fully covered highway (two RSUs per km) results in rather good results of improvement of about 12% in average, a low covered highway (one RSU every 4km) is not able to keep up with those good results and achieves an improvement rate of 5% in average. As a compromise, a coverage of one RSU every 2km, could save costs on the one hand, but still produce acceptable results on the other hand (10% improvement in average). However, instead of using ITS-G5 communication at all, it has been shown that communicating speed advices or speed limits to the vehicles via the cellular link, e.g. using already existing communication infrastructures such as LTE, the improvement in traffic efficiency does not suffer from that choice: An improvement of 11% in average can be achieved using cellular communication.



Penetration Rate	No-Control	High RSU Coverage	Mid RSU Coverage	Low RSU Coverage	Cellular Communication
100 - 00 - 00	227 s	227 s **(0%)**	227 s **(0%)**	227 s **(0%)**	227 s **(0%)**
85 - 10 - 05	218 s	200 s **(8%)**	206 s **(6%)**	207 s **(5%)**	206 s **(6%)**
70 - 20 - 10	287 s	252 s **(12%)**	255 s **(11%)**	262 s **(9%)**	249 s **(13%)**
30 - 45 - 25	317 s	272 s **(14%)**	272 s **(14%)**	318 s **(0%)**	**274 (14%)**

Figure 65. No-control compared to different RSUs coverage. Aggregated results

7.2.6. Traffic state estimation for mixed vehicle traffic

Real-time traffic state estimation utilizing limited traffic data is of major importance, not only for traffic monitoring but also for traffic control. In conventional traffic, real-time traffic data is provided by spot sensors positioned at appropriate locations on the highway. To keep the related installation and maintenance costs limited, estimation schemes are also employed. Currently and in the years to come, an increasing number of vehicles become "connected", i.e. enabled to send (and receive) real-time information to (and from) a local or central monitoring (and control) centre (V2I) or other vehicles (V2V). Connected vehicles may communicate their position, speed and other relevant information, i.e. they can act as mobile sensors. This allows for a sensible reduction (and, potentially, elimination) of the necessary number of spot sensors, which would lead to sensible reduction of the purchase, installation and maintenance costs for traffic monitoring; while, at the same time, improving the estimation quality. Although this data fusion and traffic state estimation problem has already attracted some attention by the scientific community, there is a need for further developments towards robust and practice relevant tools. These tools should exploit information provided by connected vehicles and should reduce the need for spot sensor measurements under all penetration rates of connected vehicles.

Deliverable 2.5 presented practicable and robust traffic flow estimation methods for mixed traffic, comprising conventional and connected vehicles at any penetration rate. The estimation tools receive information provided by connected vehicles and fuse it with measurements stemming from a minimum number (necessary for flow observability) of spot sensor measurements. They deliver in real-time reliable estimates of traffic density and traffic flow by segment and even by lane.

A software tool has been developed within WP2 that implements the estimation strategies in a generic way. The strategy has now been evaluated using the co-simulation environment for the Spanish test site utilizing a realistic demand profile for the mainstream and a synthetic demand for the most downstream on-ramp. The full population of vehicles includes the following groups: (slow/fast) cars (vehicles), trailers and motorcycles. The user is able to easily modify the penetration rate for CVs (conventional vehicles), CCVs (connected conventional vehicles) and AVs (automated vehicles) among all vehicles. The network topology as well as all other configuration parameters for the estimator are given by the user through an input file.

The following subsections present results for mixed traffic and for a) the cross-lane case; and b) the per-lane case. Based on the presented results, we can claim that the developed tool for the cross-lane case has reached maturity allowing for immediate exploitation and can provide a necessary basis for real-time control tasks with various requirements regarding the estimation granularity, the estimated variables or the underlying architecture.

7.2.6.1 The cross-lane case

This subsection presents evaluation results for a traffic flow estimation method presented in Deliverable 2.5 for mixed traffic and for the cross-lane case.

The highway is subdivided into segments (e.g. of some 500 m in length). The proposed estimation algorithm is a Kalman filter based estimator and is able to estimate the density of each segment and the flow of any unmeasured ramp (on-ramp or off-ramp) per estimation interval (multiple of the measurement interval) based on the following measurements obtained per measurement interval:

- The average speed of connected vehicles per segment and per estimation interval.
- The flow of vehicles at the entry of the considered highway stretch via fixed flow sensors.
- The flow of vehicles for any measured ramps via fixed flow sensors.
- The flow at the exit of the considered highway stretch as well as additional mainstream flow measurements from any highway segment between two consecutive unmeasured ramps, via corresponding fixed flow sensors.

In order to thoroughly examine the effectiveness, sensitivity and further aspects of the estimation scheme in a microscopic simulation environment, the co-simulation environment is employed for the Spanish test site that is a highway stretch of about 19 km. The stretch has been divided into 38 segments with a length that ranges from 0.4 to 0.7 km. However, most of the segments have a length of 0.5 km. Segments 1 to 4 have 3 lanes while all the other segments have 4 lanes. Three on-ramps are positioned at the end of segments 4, 20 and 30 while 2 off-ramps are positioned at the end of segments 18 and 28, respectively. In order to make this evaluation more challenging, we will assume that none of the ramps is measured. Only the absolutely necessary mainstream flow measurements will be considered in order to guarantee observability. These include the aggregated (over all lanes) flow measurements at the entry of the highway, and at the end of segments 5, 19, 25, 29 and 34.

Finally, the average speed of connected vehicles per segment is also available. The measurement and estimation intervals are both set equal to 10 sec.

Five different sets of penetration rates (CV-CCV-AV) will be considered. These are the following: i) (94-4-2); ii) (85-10-5); iii) (70-20-10); iv) (55-30-15); and v) (30-45-25). As AVs are connected as well, the above mentioned sets correspond to the following penetration rates of connected vehicles: 6%, 15%, 30%, 45, and 70%. Ten replications are conducted for each penetration rate for a simulation horizon of 3 hours. Each replication has the same average demand profile and the same mean values for all vehicle-related parameters. Free-flow as well as congested traffic conditions are present in the highway stretch. As the penetration rate of AVs increases, the congestion created at the merge area of the third on-ramp lasts more time and spills back covering bigger parts of the highway stretch.

The ground truth in our experiments, considered for evaluating the performance of the proposed estimation scheme, is represented by the density of each segment and the ramp flows. In order to evaluate the estimation results, the following performance index, known as Coefficient of Variation (CV) of the estimated density $\hat{\rho}_i(k)$ (at segment i at time step k) with respect to the ground truth density $\rho_i(k)$, is used

$$CV_\rho = \frac{\sqrt{\frac{1}{KN}\sum_{k=1}^{K}\sum_{i=1}^{N}\left[\hat{\rho}_i(k)-\rho_i(k)\right]^2}}{\frac{1}{KN}\sum_{k=1}^{K}\sum_{i=1}^{N}\rho_i(k)} \tag{4}$$

where K is the number of estimation intervals and N the number of segments. Similarly, for the unmeasured ramp flows estimation, the CV of the estimated ramp flows $\hat{q}_i(k)$ (at segment i at time step k) with respect to the ground truth ramp flows $q_i(k)$, is given by the following equation

$$CV_{r,s} = \frac{\sqrt{\frac{1}{K(l_r+l_s)}\sum_{k=1}^{K}\sum_{i=1}^{l_r+l_s}\left[\hat{q}_i(k)-q_i(k)\right]^2}}{\frac{1}{K(l_r+l_s)}\sum_{k=1}^{K}\sum_{i=1}^{l_r+l_s}q_i(k)} \tag{5}$$

where l_r and l_s are the numbers of unmeasured on-ramp flows and off-ramp flows, respectively.

The estimation scheme includes 3 parameters (σ_ρ, $\sigma_{r,s}$, and σ_R) for which some rough tuning has been performed and has resulted the use of the set (10 veh/km, 0.1 veh/km and 100 veh/h). Performance comparison (averages over 10 replications) of the density and ramp flow estimations for different values of the parameters are presented for all penetration rates in *Figure 66*. It is evident in the plots that the performance of density estimation is highly insensitive to the values of the filter parameters. Ramp flow estimation is shown to be more sensitive, especially for low penetration rates of connected vehicles.

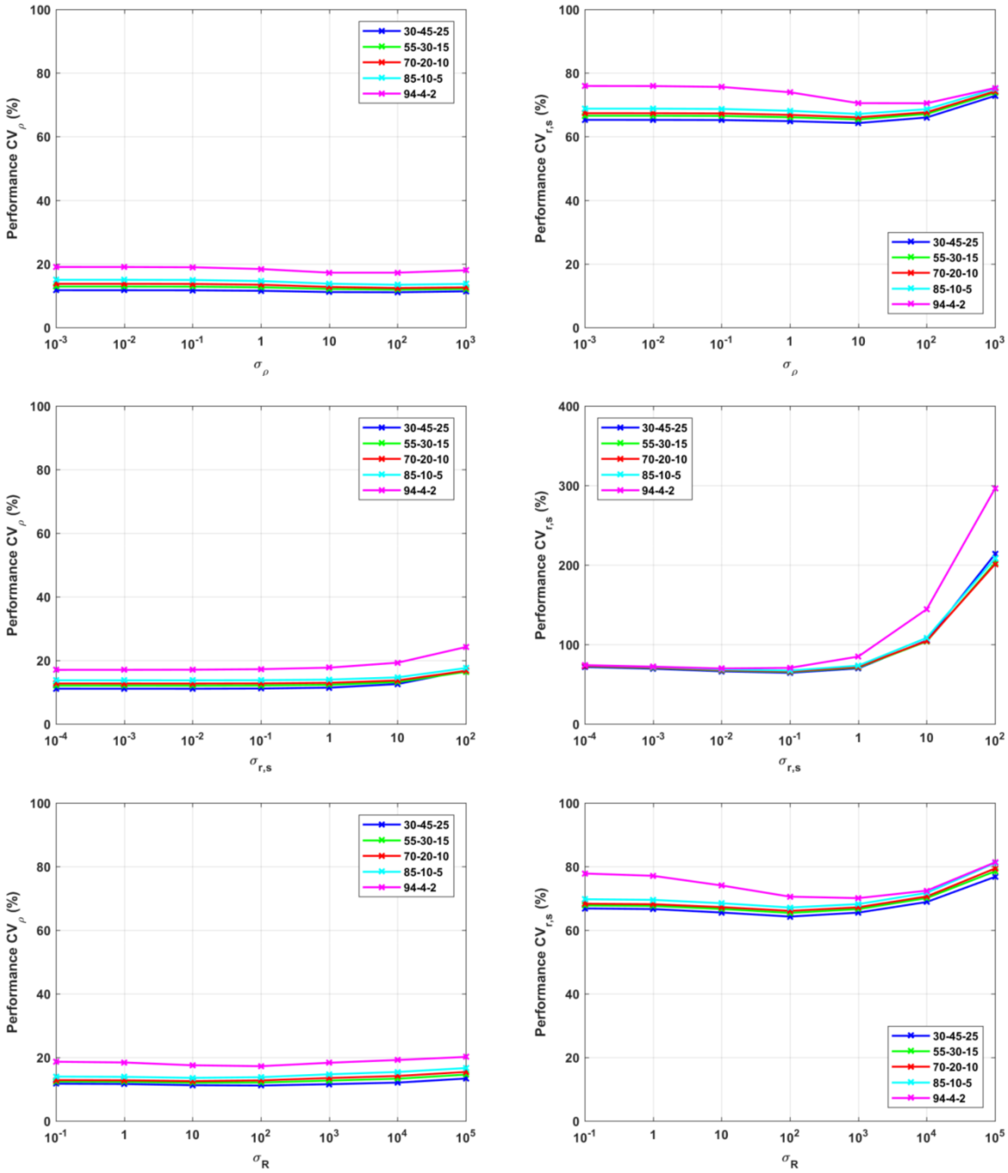


Figure 66. Performance comparison of the density (left) and ramp flow (right) estimations for different values of the parameters σ_ρ (top), $\sigma_{r,s}$ (middle), and σ_R (bottom)

The performance indices of the estimation (averages over 10 replications) for the tuned parameters per penetration rate are presented also in *Figure 67*. It can be observed that the performance of the estimator decreases slightly for low penetration rates of connected vehicles.

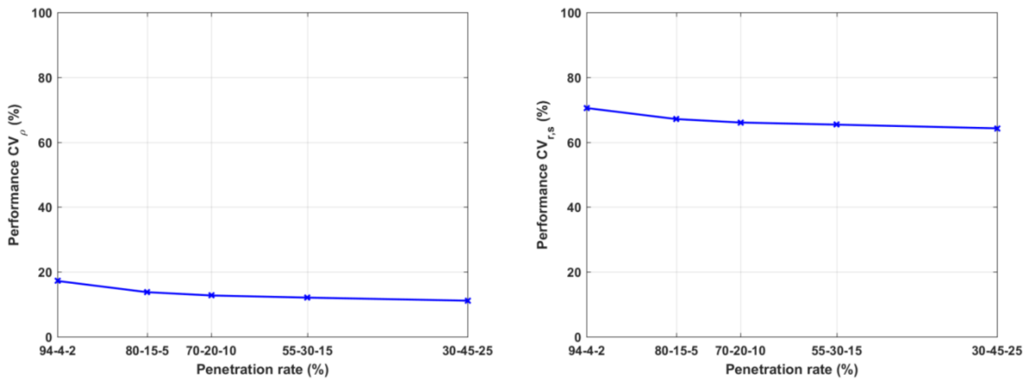
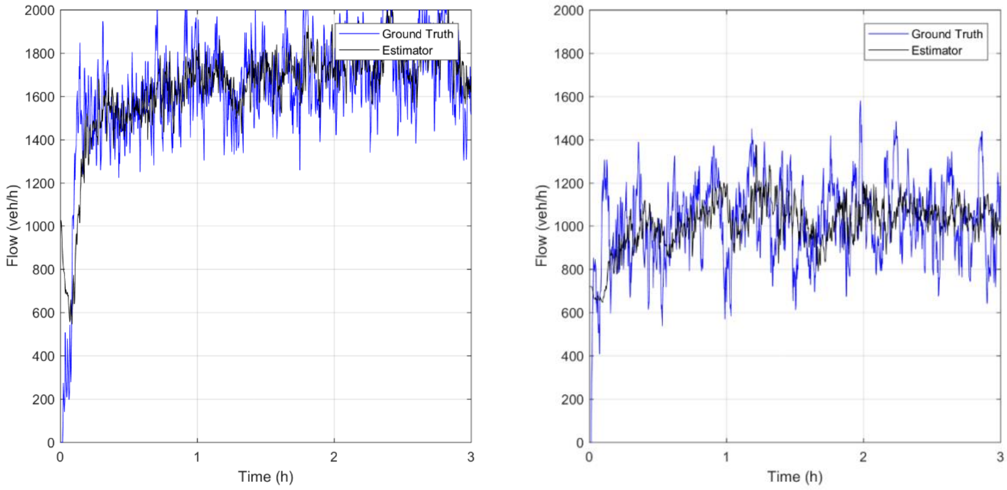


Figure 67. Performance indices of density (left) and ramp flow (right) estimations calculated for various penetration rates

The results of the estimation of ramp flows and densities for one of the replications with a 70% penetration rate of connected vehicles (30-45-25) are shown in *Figure 68* and *Figure 69* respectively. It is evident from the plots that the proposed scheme successfully estimates and dynamically tracks both densities and ramp flows under various traffic conditions, including congested and free-flow conditions. Note also the fast convergence of the estimates towards the real values, starting from remote initial values, which were deliberately chosen far from the real values in order to test the filter's convergence properties. The results of the estimation of density for specific segments (segments 20, i.e. the merge area for the second on-ramp, and segment 30, i.e. the merge area for the third on-ramp where congestion starts) are shown in *Figure 70*.

The results of the estimation are equally good even for lower penetration rates. The corresponding plots are presented in Figures 71-73.



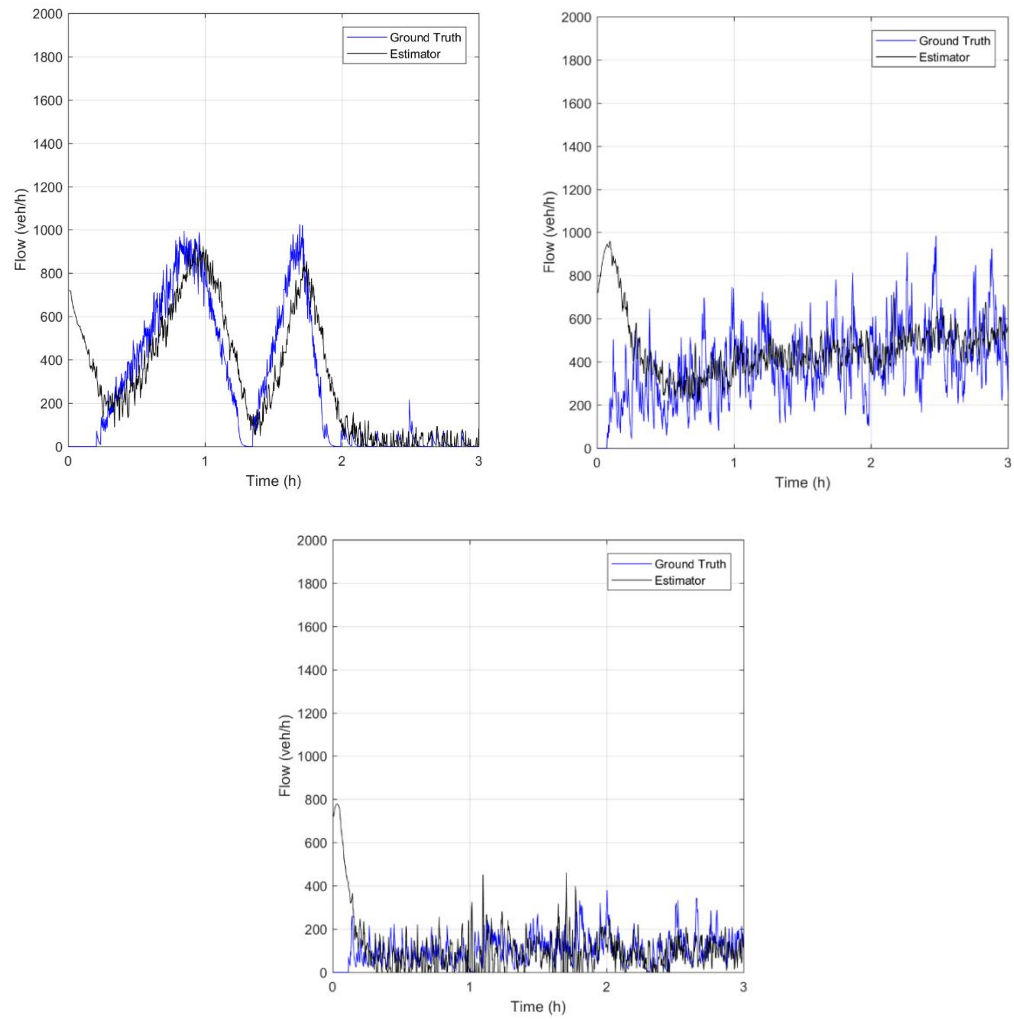


Figure 68. Comparison between real (blue line) and estimated (back line) ramp flows for all network on-ramps (3 first plots) and off-ramps (2 last plots) for mixed traffic with a 70% penetration rate (30-45-25) of connected vehicles

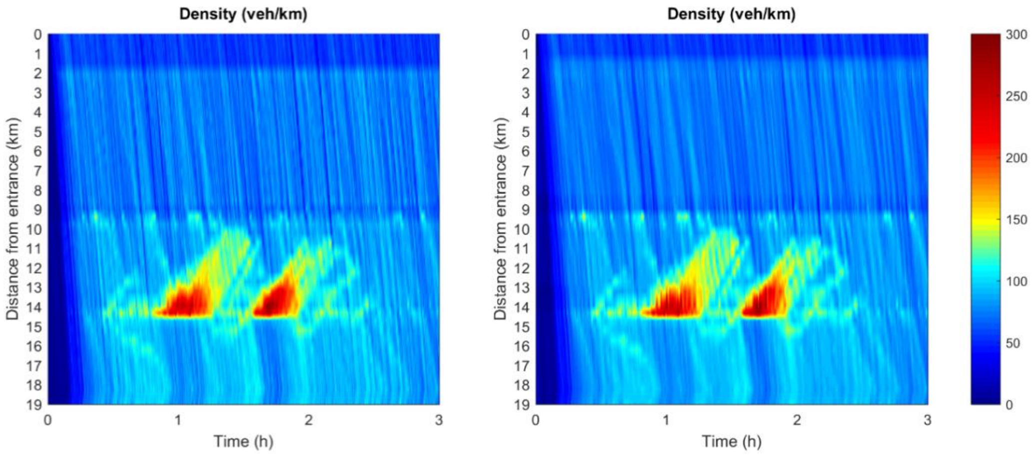


Figure 69. Comparison between real (left) and estimated (right) density for all network for mixed traffic with a 70% penetration rate (30-45-25) of connected vehicles

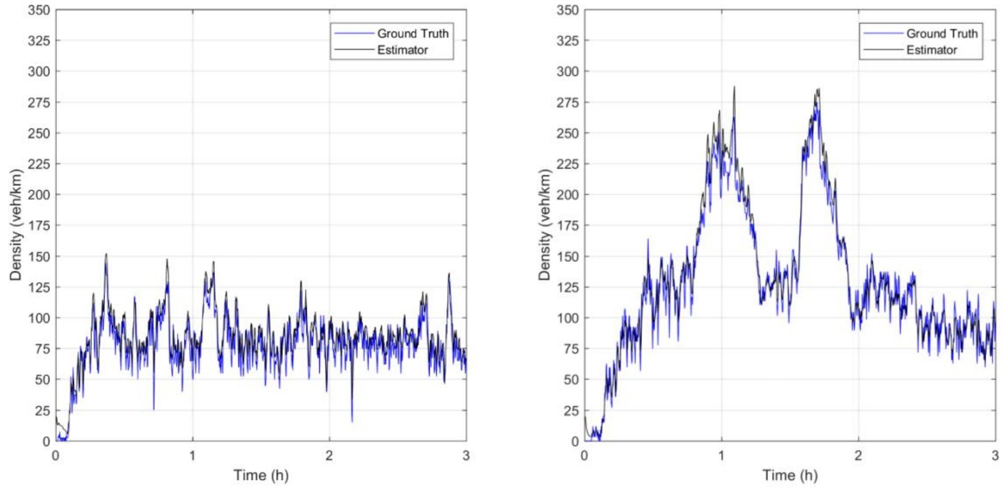
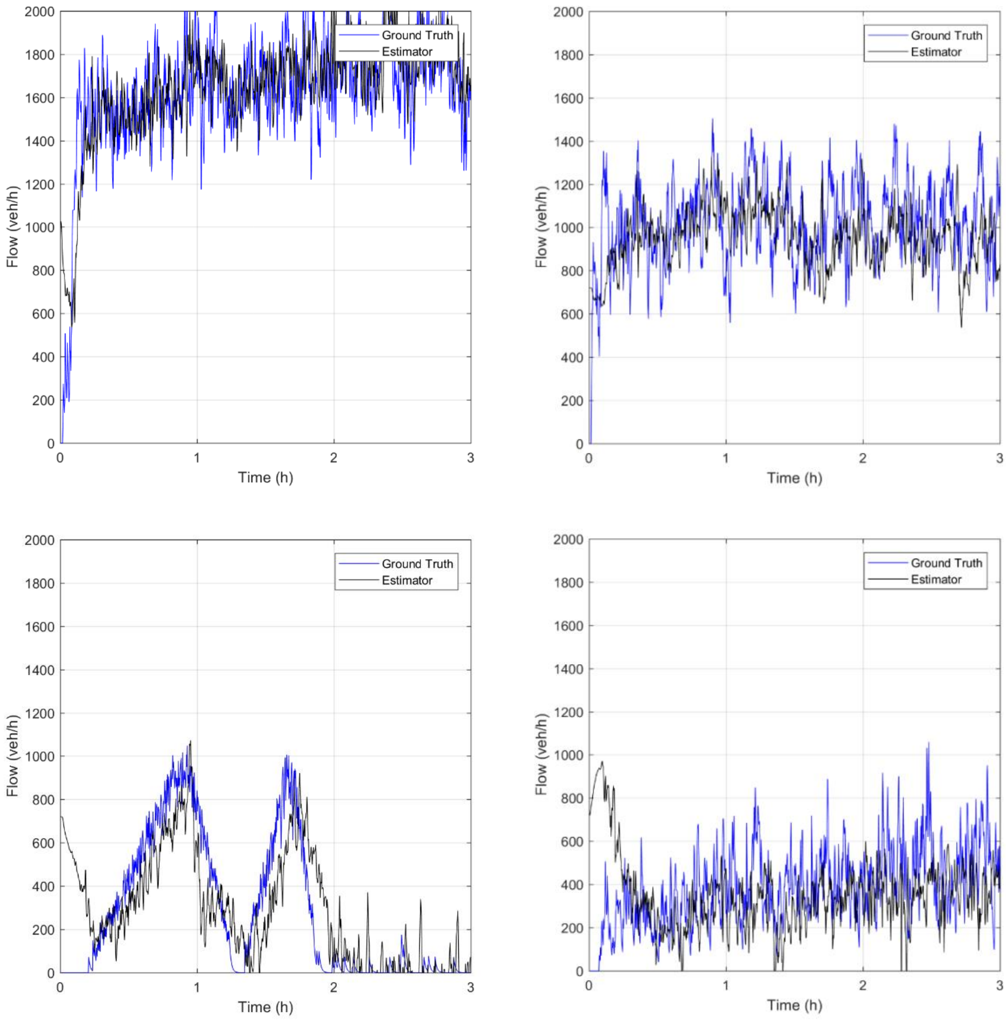


Figure 70. Comparison between real (blue line) and estimated (back line) density for segment 20 (left) and segment 30 (right) for mixed traffic with a 70% penetration rate (30-45-25) of connected vehicles



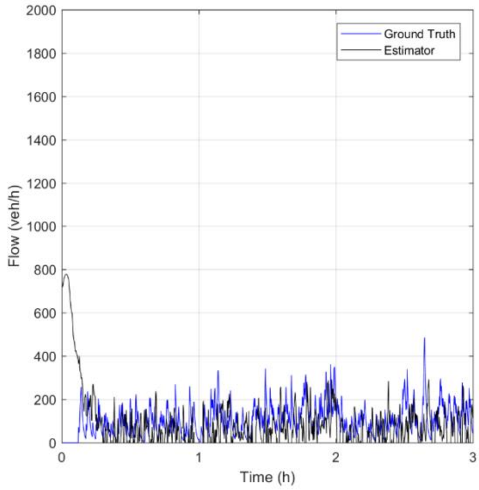


Figure 71. Comparison between real (blue line) and estimated (back line) ramp flows for all network on-ramps (3 first plots) and off-ramps (2 last plots) for mixed traffic with a 6% penetration rate (94-4-2) of connected vehicles

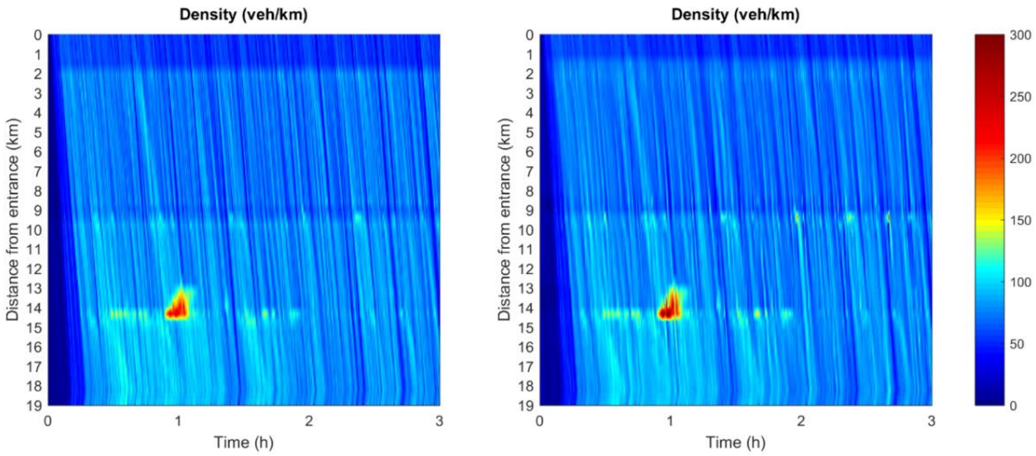


Figure 72. Comparison between real (left) and estimated (right) density for all network for mixed traffic with a 6% penetration rate (94-4-2) of connected vehicles

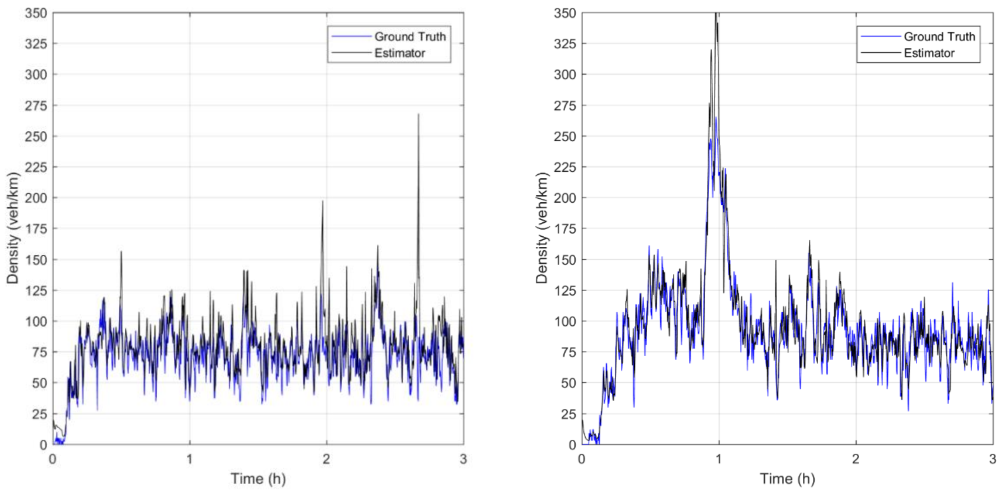


Figure 73. Comparison between real (blue line) and estimated (back line) density for segment 20 (left) and segment 30 (right) for mixed traffic with a 6% penetration rate (94-4-2) of connected vehicles

7.2.6.2 *The per-lane case*

This subsection presents evaluation results for a traffic flow estimation method presented in Deliverable 2.5 for mixed traffic and for the per-lane case.

The highway is subdivided into lanes and segments (e.g. of some 500 m in length). The proposed estimation algorithm is a Kalman filter based estimator and is able to estimate the density of each segment-lane and the flow of any unmeasured ramp (on-ramp or off-ramp) per estimation interval (multiple of the measurement interval) based on the following measurements obtained per measurement interval:

- The average speed of connected vehicles per segment-lane and per estimation interval.
- The density of connected vehicles per segment-lane and per estimation interval.
- Lateral flows of connected vehicles per segment-lane and per estimation interval.
- The flow of vehicles (per lane) at the entry of the considered highway stretch via fixed flow sensors.
- The flow of vehicles for any measured ramps via fixed flow sensors.
- The flow of vehicles (per lane) at the exit of the considered highway stretch as well as additional mainstream flow measurements (per lane) from any highway segment between two consecutive unmeasured ramps, via corresponding fixed flow sensors.

In order to thoroughly examine the effectiveness, sensitivity and further aspects of the estimation scheme in a microscopic simulation environment, the co-simulation environment is employed once more for the Spanish test site that is a highway stretch of about 19 km. The stretch has been divided into 38 segments with a length that ranges from 0.4 to 0.7 km. However, most of the segments have a length of 0.5 km. Segments 1 to 4 have 3 lanes while all the other segments have 4 lanes. Three on-ramps are positioned at the end of segments 4, 20 and 30 while 2 off-ramps are positioned at the end of segments 18 and 28, respectively. Again, in order to make this evaluation more challenging, we will assume that none of the ramps is measured. Only the absolutely necessary mainstream flow measurements will be considered in order to guarantee observability. These include the flow measurements (per lane) at the entry of the highway, and at the end of segments 6, 19, 25, 29 and 34. Finally, the average speed, density and lateral flows of connected vehicles per segment-lane are also available. The measurement and estimation intervals are both set equal to 10 sec.

Five different sets of penetration rates (CV-CCV-AV) will be considered. These are the following: i) (94-4-2); ii) (85-10-5); iii) (70-20-10); iv) (55-30-15); and v) (30-45-25). As AVs are connected as well, the above mentioned sets correspond to the following penetration rates of connected vehicles: 6%, 15%, 30%, 45, and 70%. Ten replications are conducted for each penetration rate for a simulation horizon of 3 hours. Each replication has the same average demand profile and the same mean values for all vehicle-related parameters. Free-flow as well as congested traffic conditions are present in the highway stretch. As the penetration rate of AVs increases, the congestion created at the merge area of the third on-ramp lasts more time and spills back covering bigger parts of the highway stretch.

The ground truth in our experiments, considered for evaluating the performance of the proposed estimation scheme, is represented by the density of each segment-lane and the ramp flows. In order to evaluate the estimation results, the following performance index, known as Coefficient of Variation (CV) of the estimated density $\hat{\rho}_{i,j}(k)$ (at segment i at time step k) with respect to the ground truth density $\rho_i(k)$, is used

$$CV_\rho = \frac{\sqrt{\frac{1}{KNM}\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M}\left[\hat{\rho}_{i,j}(k)-\rho_{i,j}(k)\right]^2}}{\frac{1}{KNM}\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{M}\rho_{i,j}(k)} \tag{6}$$

where K is the number of estimation intervals, N the number of segments and M is the number of lanes. Similarly, for the unmeasured ramp flows estimation, the CV of the estimated ramp flows $\hat{q}_i(k)$ (at segment i at time step k) with respect to the ground truth ramp flows $q_i(k)$, is given by the following equation

$$CV_{r,s} = \frac{\sqrt{\frac{1}{K(l_r+l_s)}\sum_{k=1}^{K}\sum_{i=1}^{l_r+l_s}\left[\hat{q}_i(k)-q_i(k)\right]^2}}{\frac{1}{K(l_r+l_s)}\sum_{k=1}^{K}\sum_{i=1}^{l_r+l_s}q_i(k)} \tag{7}$$

where l_r and l_s are the numbers of unmeasured on-ramp flows and off-ramp flows, respectively.

The estimation scheme includes 3 parameters (σ_ρ, $\sigma_{r,s}$, and σ_R) for which some rough tuning has been performed and has resulted the use of the set (1 veh/km, 100 veh/h and 100 veh/h). The performance indices of the estimation (averages over 10 replications) for the tuned parameters per penetration rate are presented in *Figure 74* (blue curves). It can be observed that the performance of the estimator decreases slightly for low penetration rates of connected vehicles but there is no performance index reported for the lowest penetration rate (94-4-2). Also, in general the performance indices are slightly worse compared to the ones achieves for the cross-lane estimations (see *Figure 67*). When looking at the details, we concluded that the lateral flow information (lane changes) delivered by the connected vehicles, for the lowest penetration rate (94-4-2), is not representative for the whole population, because it does not include information from trailer that are present in the slow lanes and have a completely different behaviour when it comes to the number and frequency of lane changes performed. This caused some instability problems for the estimator. Based on the above, we decided to run all the scenarios again including the same penetration of connectivity also for trailers, i.e. if the penetration rate for CV-CCV-AV is e.g. 94-4-2, then the penetration rate for CT-CCT is 94-6 (where CT stand for Conventional Trailers and CCT stands for Connected Conventional Trailers). The performance indices of the estimation (averages over 10 replications) per penetration rate are presented in Figure 74 (red curves) and they are just slight improved compared to the previous case, delivering also results for the lowest penetration rate of connected vehicles considered.

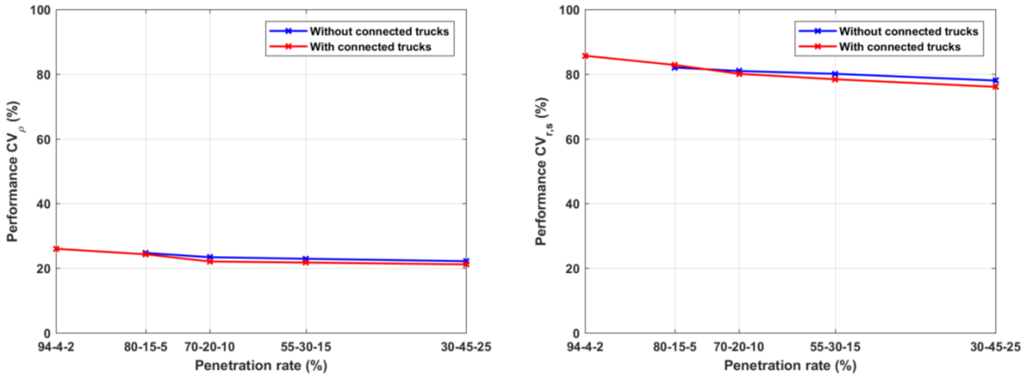


Figure 74. Performance indices of density (left) and ramp flow (right) estimations calculated for various penetration rates

The results of the estimation of ramp flows and densities for one of the replications with a 70% penetration rate of connected vehicles (30-45-25) are shown in *Figure 75* and *Figure 76*, respectively. It is evident from the plots that the estimation obtained for the ramp flows is not really good; some bias in the estimation is present for the case of the on-ramps. However, one could run in parallel the cross-lane estimator that is delivering very good estimates for the ramp flows (see results in previous sub-section). On the other hand, the proposed scheme successfully estimates and dynamically tracks density per lane under various traffic conditions, including congested and free-flow conditions. Note that density (expressed in veh/km/lane) in lane 1, and partly also in lane 2, is lower compared to density in lanes 3 and 4, as lanes 1 and 2 include a lot of trailers, i.e. lanes 1 and 2 are equally "dense" with lower numbers of vehicles (trailers). The results of the estimation of density for specific segment-lanes (segment-lane 20-2, i.e. next to the merge area for the second on-ramp, and segment-lane 30-1, i.e. the merge area for the third on-ramp where congestion starts) are shown in *Figure 77*.

The results of the estimation for the density per lane are equally good even for lower penetration rates. The corresponding plots are presented in *Figure 78* and *Figure 79*.

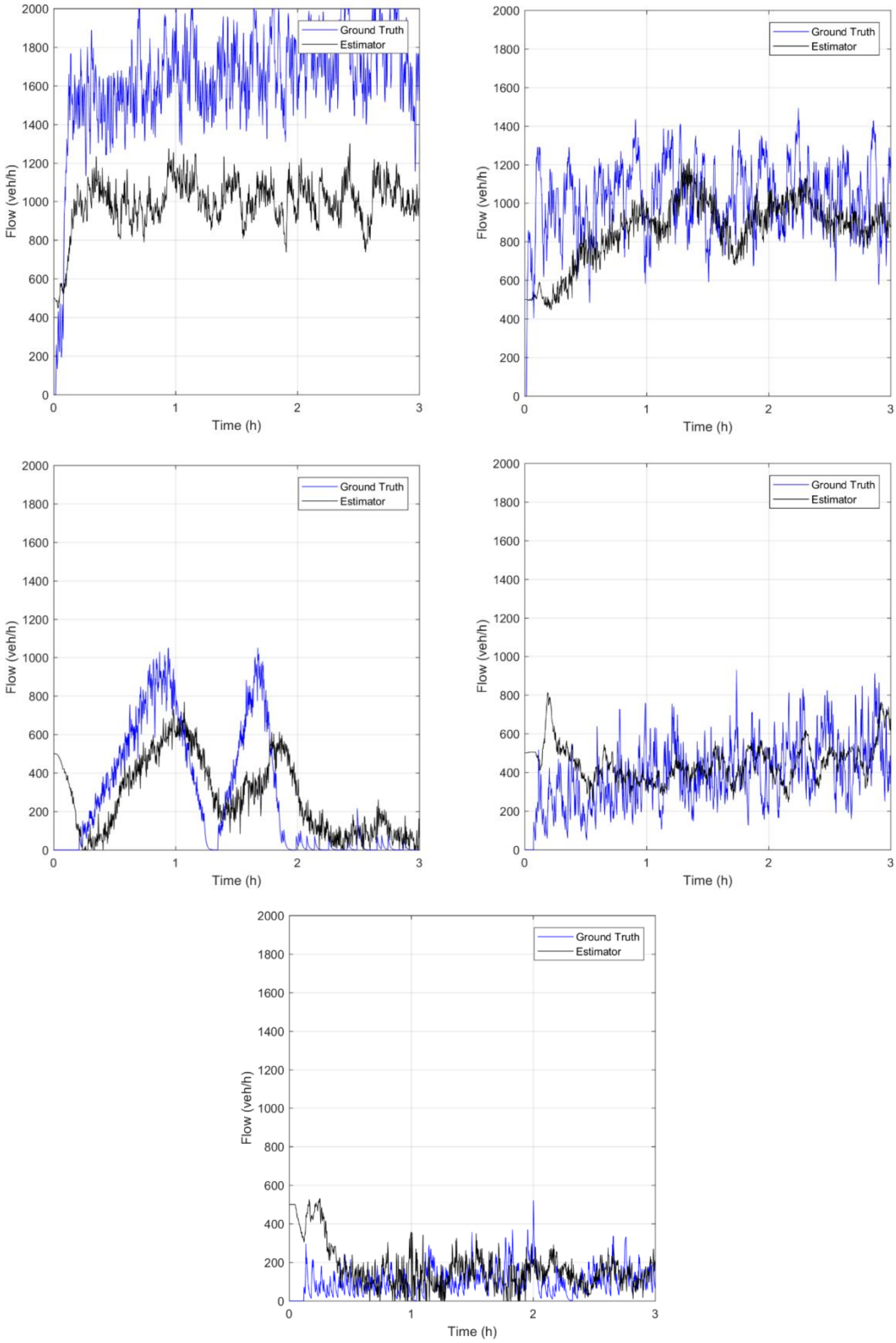


Figure 75. Comparison between real (blue line) and estimated (back line) ramp flows for all network on-ramps (3 first plots) and off-ramps (2 last plots) for mixed traffic with a 70% penetration rate (30-45-25, 30-70) of connected vehicles and trucks

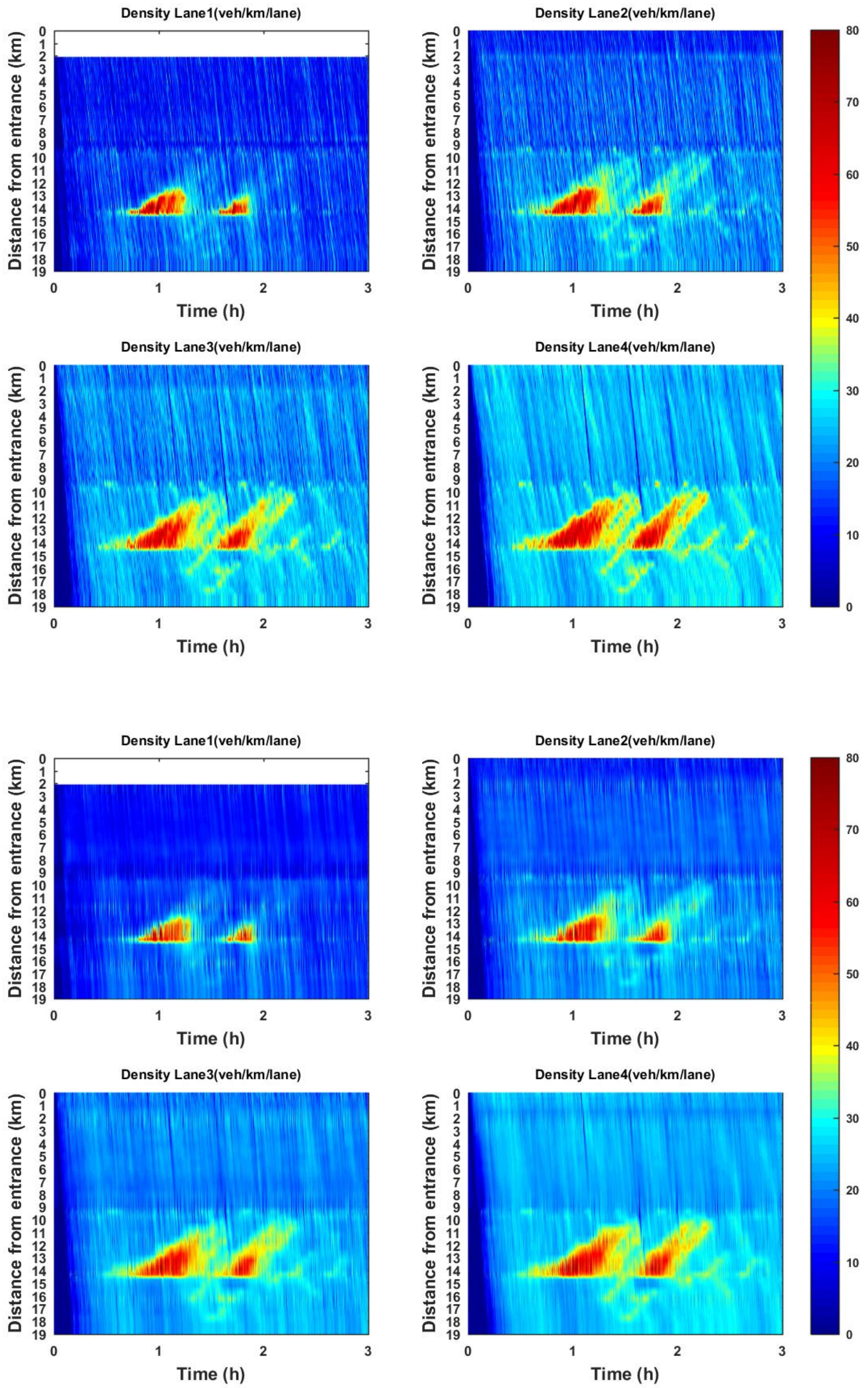


Figure 76 .Comparison between real (top) and estimated (bottom) density for all lanes for mixed traffic with a 70% penetration rate (30-45-25, 30-70) of connected vehicles and trucks

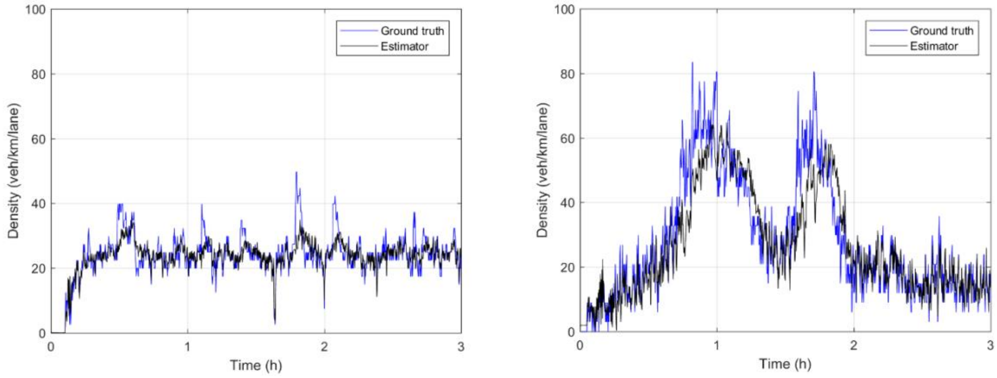
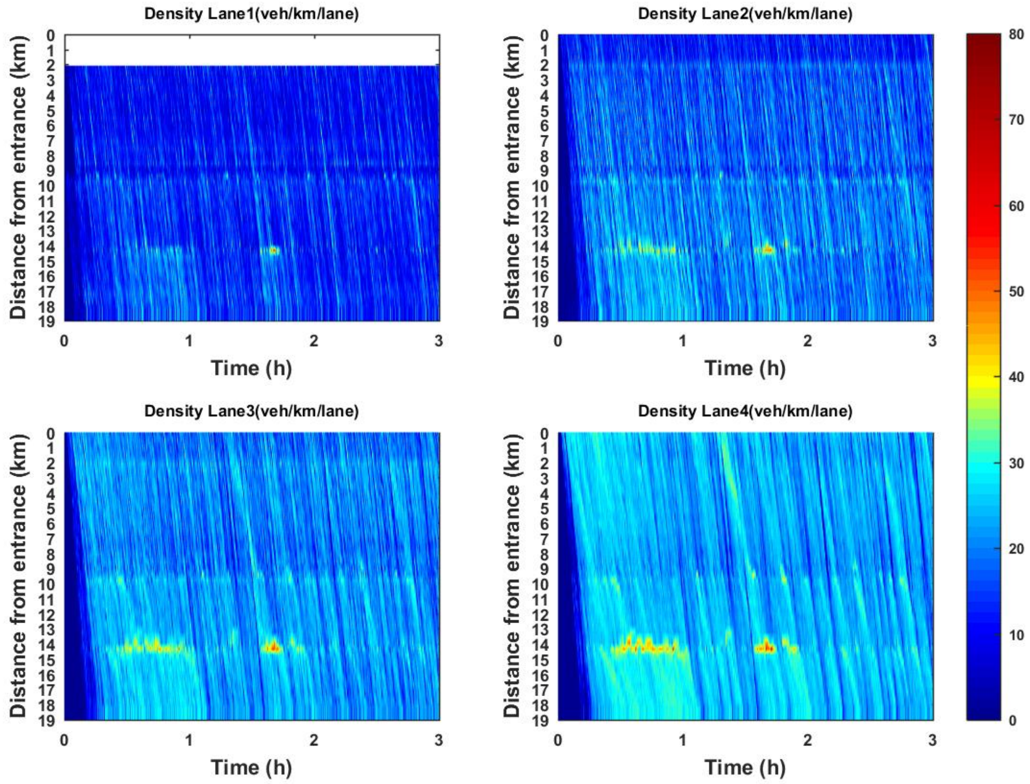


Figure 77 . Comparison between real (blue line) and estimated (back line) density for segment-lane 20-2 (left) and segment-lane 30-1 (right) for mixed traffic with a 70% penetration rate (30-45-25, 30-70) of connected vehicles and trucks



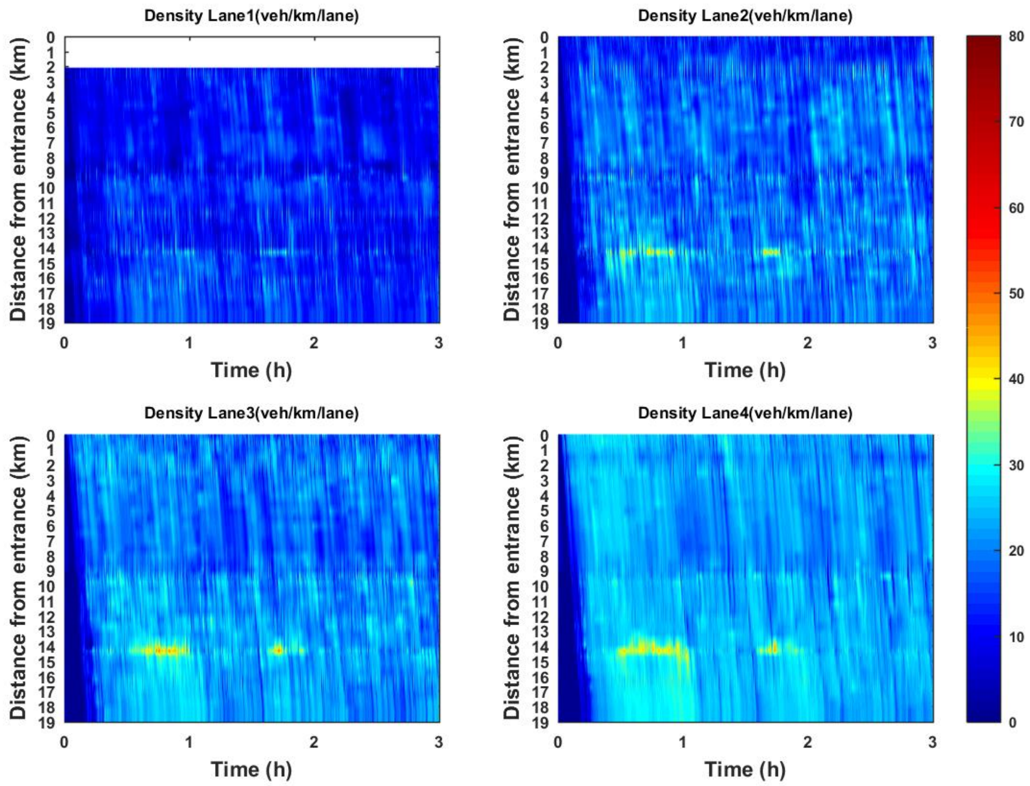


Figure 78 .Comparison between real (top) and estimated (bottom) density for all lanes for mixed traffic with a 6% penetration rate (94-4-2, 94-6) of connected vehicles and trucks

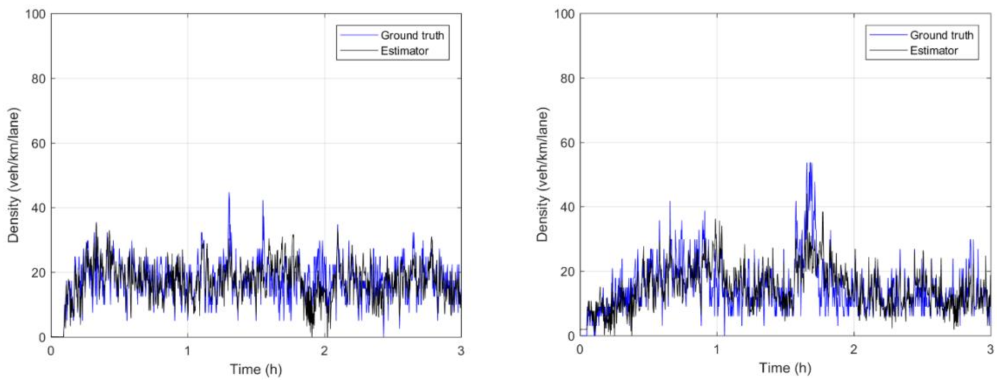


Figure 79 . Comparison between real (blue line) and estimated (back line) density for segment-lane 20-2 (left) and segment-lane 30-1 (right) for mixed traffic with a 6% penetration rate (94-4-2, 94-6) of connected vehicles and trucks

7.3 Microscopic Simulations Impact on Traffic Efficiency of Dedicated Lane Assignment Control

The impact of setting (permanent) dedicated lanes for AVs on traffic flow throughput has been investigated recently using appropriate macroscopic modelling of AVs in heterogeneous traffic flow [8], [9]. Simulation results from these studies indicate that at a low AV penetration rate, setting AV dedicated lanes deteriorates the performance of the overall traffic flow throughput, particularly under a low density level. When AVs reach a dominant role in the mixed flow, the merits of setting dedicated lanes also decrease. The benefit of setting an AV dedicated lane can only be obtained within a medium density range. AV penetration rate and individual AV performance are significant factors that decide the performance of AV dedicated lane. The higher level of performance the AVs could achieve, the greater benefit will be attained through the deployment of AV dedicated lane. Of course, the level of performance of AVs depends on the various settings, e.g. time-gap, maximum acceleration, reaction time. Besides, the performance of AV dedicated lane can be improved through setting a higher speed limit for AVs on the dedicated lane than vehicles on other normal lanes.

Some other papers study the impact of deploying permanent dedicated lanes for AVs on a network level assuming various penetration rates. These studies are using macroscopic models and a lot of related assumptions and reach similar conclusions.

In a mixed traffic environment with a penetration rate varying within the day, a dynamic assignment of a dedicated lane to AVs sounds more appropriate than a permanent one. A simple threshold-based control strategy has been developed for dynamic lane assignment (DLA) to AVs and was presented in Deliverable 2.5. Of course, connectivity is a prerequisite in order to communicate related DLA activation and deactivation messages to AVs.

The concept is general and considers a motorway stretch divided into n segments and a flow capacity that is obtained around a critical density ρ_{cr}. Only one specific lane can be assigned to AVs, as long as some conditions are met. The location of the lane (e.g. right or left lane) and the minimum number of consecutive segments ($\leq n$) that are required for the activation of a dedicated lane are preselected by the operator considering traffic management goals as well as safety parameters.

Some threshold based conditions are checked for the measured (or estimated) density every control period for all segments on which a dedicated lane is not already active. If all conditions are met for a segment, then this segment becomes a candidate for application of the dedicated lane for AVs. These conditions take into account the penetration rate of AVs and make sure that the logic is applied only for densities that are above some thresholds. They also take into account the capacity of the segments, the capacity of the dedicated lane and the capacity of the rest of the lanes left for conventional traffic.

If a segment was a candidate in the previous control period, then some other threshold based conditions are checked. If any of these conditions are true for a segment, then this segment is not any more a candidate segment for application of the dedicated lane for AVs. Appropriately thresholds have to be selected such that $\rho_{deact}^{min} < \rho_{act}^{min} < \rho_{act}^{max} < \rho_{deact}^{max} < \rho_{cr}$ holds in order to add some hysteresis between activation and deactivation actions.

If a number of consecutive segments are candidates and this number is greater than or equal to the minimum number of segments required for the activation of a dedicated lane, then these segments become active. Otherwise they are not active. Consecutive active segments form a cluster that is used to assign a lane to AVs. These segments remain part of the cluster as long as they are active and for a period that is at least equal to a predefined minimum period in order to avoid weaving phenomena that are expected during activation and deactivation of the dedicated lane on the segments.

Every time that a new candidate segment is attached to a cluster of active segments, the timer used to count the active period is reset for all segments that are necessary to form a dedicated lane with at least the minimum number of segments required in a cluster that contains the new candidate.

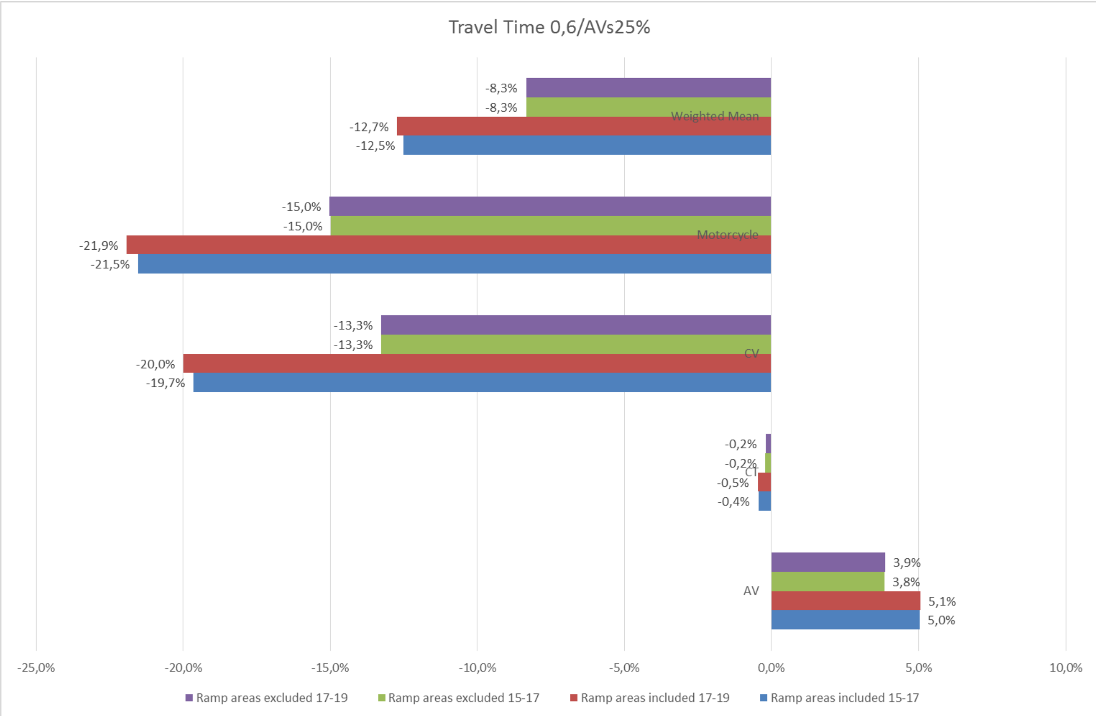
A software tool has been developed within WP2 that implements the control strategy in a generic way. The strategy has now been evaluated using the co-simulation environment for the Spanish test site. All configuration parameters are given by the user through an input file. In our experiments, the time period for updating decisions according to the above has been set equal to 1 minute. Exponentially smoothed measurements have been used in order to avoid possible oscillations or false alarms. The minimum number of consecutive segments required for activation has been set to 5 segments, while the minimum number of active control steps has been set to 5 steps that correspond to 5 minutes. The lane that is assigned to AVs is always the fast lane (left lane for the network studied). This decision was taken due to the high penetration of trailers that occupy a big portion of the slow lane. A realistic demand profile has been used for (slow/fast) cars (vehicles), trailers and motorcycles. The user is able to easily modify the penetration rate for CVs, CCVs and AVs among all vehicles. In all simulations performed for this controller, no CCVs have been considered. The penetration rate of AVs among vehicles has been set initially equal to 25%, as 34 out of the 38 segments of the motorway stretch considered have 4 lanes. Of course, the penetration rate of AVs among the full population of vehicles trailers and motorcycles is in this case well below 25%. This is expected to very beneficial for AVs and less beneficial the rest of the traffic that will have to occupy the rest of the lanes. That is why all simulations where also performed with an increase penetration rate (30%) of AVs among vehicles so as to achieve an average penetration among the full population that is around 25%.

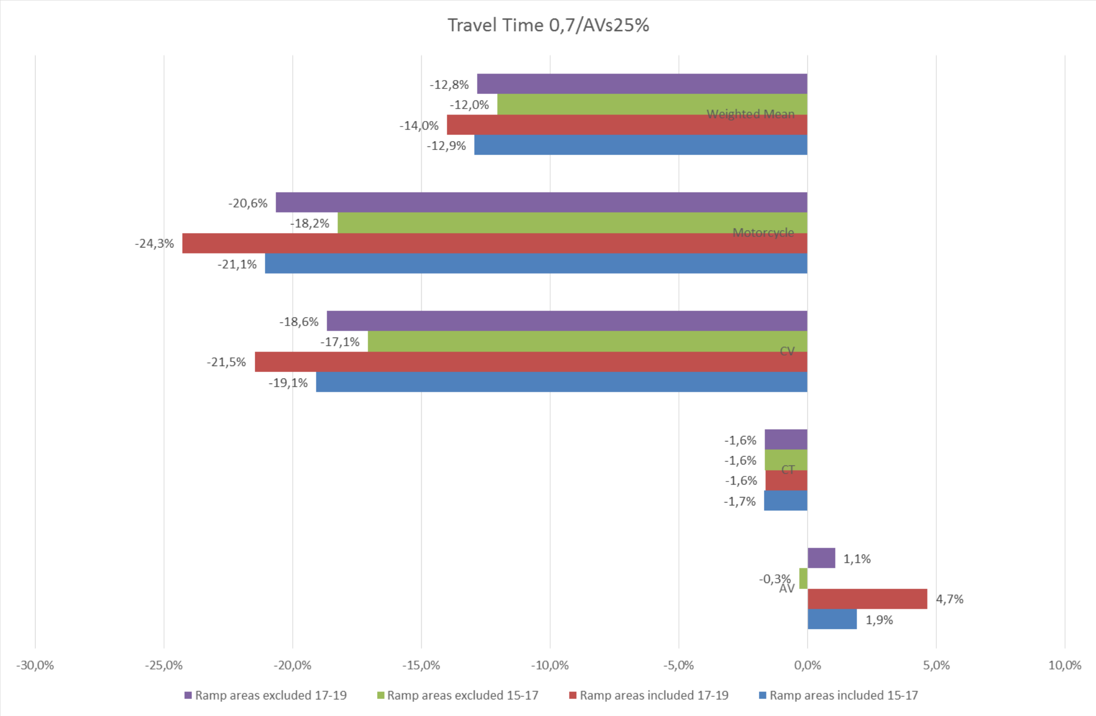
Adequate physical infrastructure adaptations have been considered by the co-simulation environment in order to achieve availability and consistency of information for all types of vehicles. CVs can be informed using VMSs at the beginning of each segment, while AVs receive the information as well specific lane-change advices via communication well in advance. As discussed already above, weaving phenomena are expected during activation and deactivation of the dedicated lane on the segments. These weaving phenomena are due to the reshuffling that is necessary in order to get all vehicles on the lanes that have been assigned to them. As a result, when density values are high these weaving phenomena lead to congestion and increase of density values even more. The dedicated lane is deactivated if the whole phenomenon is observable by the controller. However, there are cases where congestion is created upstream of the already assigned lane and, as a result, the phenomenon is not observed by the controller in order to terminate the assignment.

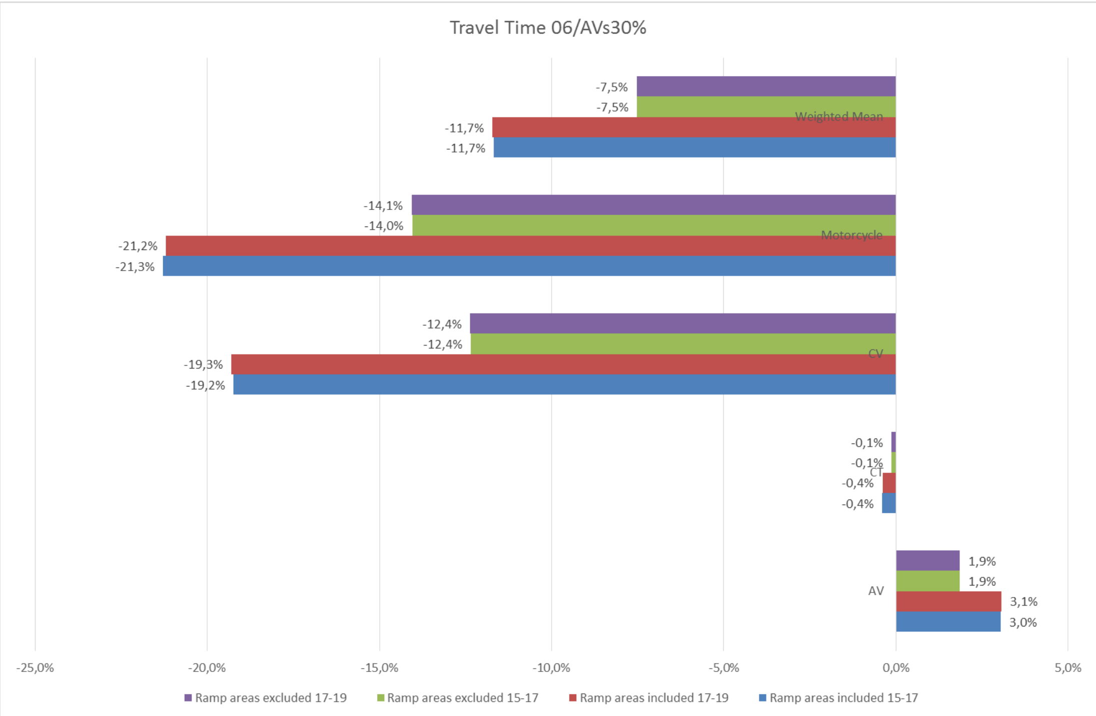
Based on the above findings, it has been decided to continue testing the DLA controller using reduced (scaled-down) demand profiles. The scaling factors utilized where either equal to 0.6 or equal to 0.7. While assigning the fast lane to AVs, two different cases have been considered with respect to the areas around sets of on/off-ramps, i.e. segments 18-21 and segments 28-31. In the first case, assignment of the fast lane is possible on all segments. In the second case considered, assignment is not possible on the above mentioned segments.

As already discussed above, the benefit of setting an AV dedicated lane can only be obtained within a medium density range. This is why the min threshold values, $\rho_{deact}^{\min}$ and $\rho_{act}^{\min}$, have been set equal to 4 veh/km/lane and 6 veh/km/lane, respectively, while the max threshold values, ρ_{act}^{max} and ρ_{deact}^{max}, have been set equal to 15 veh/km/lane and 17 veh/km/lane, respectively. A second set of simulations has been performed where the max threshold values were increased by 2 veh/km/lane.

The above mentioned 4 dimensions of different parameters used, i.e. scaling of traffic demand, penetration of AVs, inclusion or not of the areas around sets of on/off-ramps, and the values used for the density thresholds, lead to 16 different sets of simulations. For each one of these sets, 10 replications have been performed and lead to the results (weighed means over 10 replications) presented in the following figures (bar charts).




Travel Time 0,7/AVs25%
-12,8%
-12,0%
Weighted Mean
-14,0%
-12,9%
-20,6%
-18,2%
Motorcycle
-24,3%
-21,1%
-18,6%
-17,1%
CV
-21,5%
-19,1%
-1,6%
-1,6%
CT
-1,6%
-1,7%
1,1%
-0,3%
AV
4,7%
1,9%
-30,0% -25,0% -20,0% -15,0% -10,0% -5,0% 0,0% 5,0% 10,0%
Ramp areas excluded 17-19
Ramp areas excluded 15-17
Ramp areas included 17-19
Ramp areas included 15-17


Travel Time 06/AVs30%
-7,5%
-7,5%
Weighted Mean
-11,7%
-11,7%
-14,1%
-14,0%
Motorcycle
-21,2%
-21,3%
-12,4%
-12,4%
CV
-19,3%
-19,2%
-0,1%
-0,1%
CT
-0,4%
-0,4%
1,9%
1,9%
AV
3,1%
3,0%
-25,0% -20,0% -15,0% -10,0% -5,0% 0,0% 5,0%
Ramp areas excluded 17-19
Ramp areas excluded 15-17
Ramp areas included 17-19
Ramp areas included 15-17

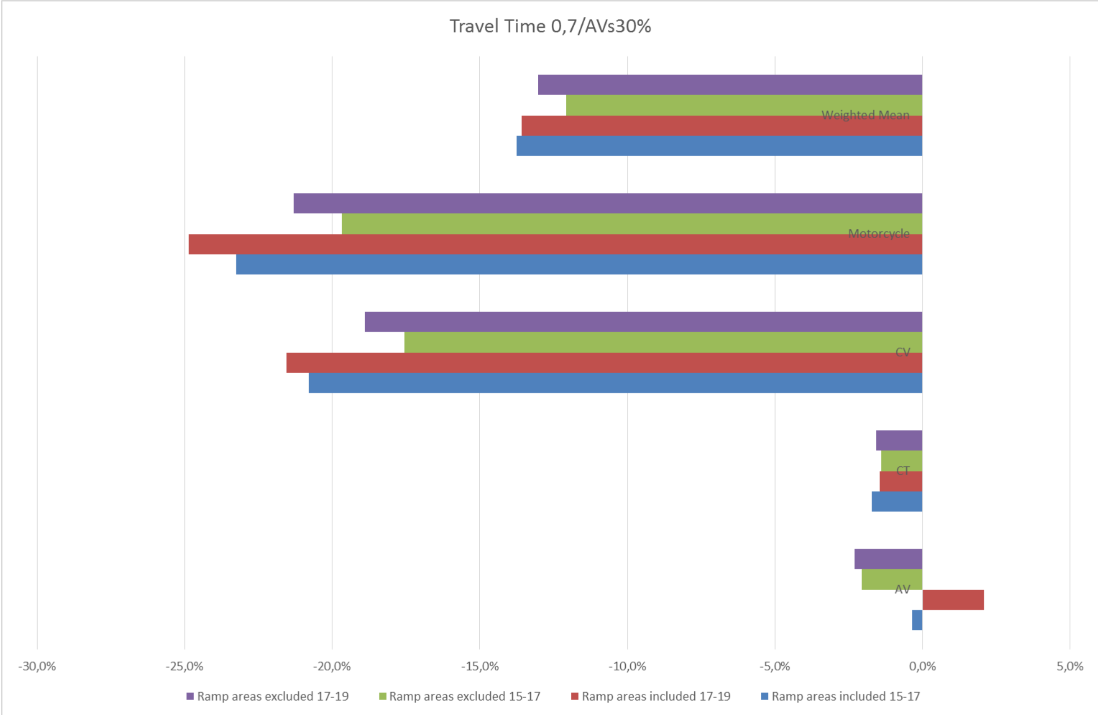
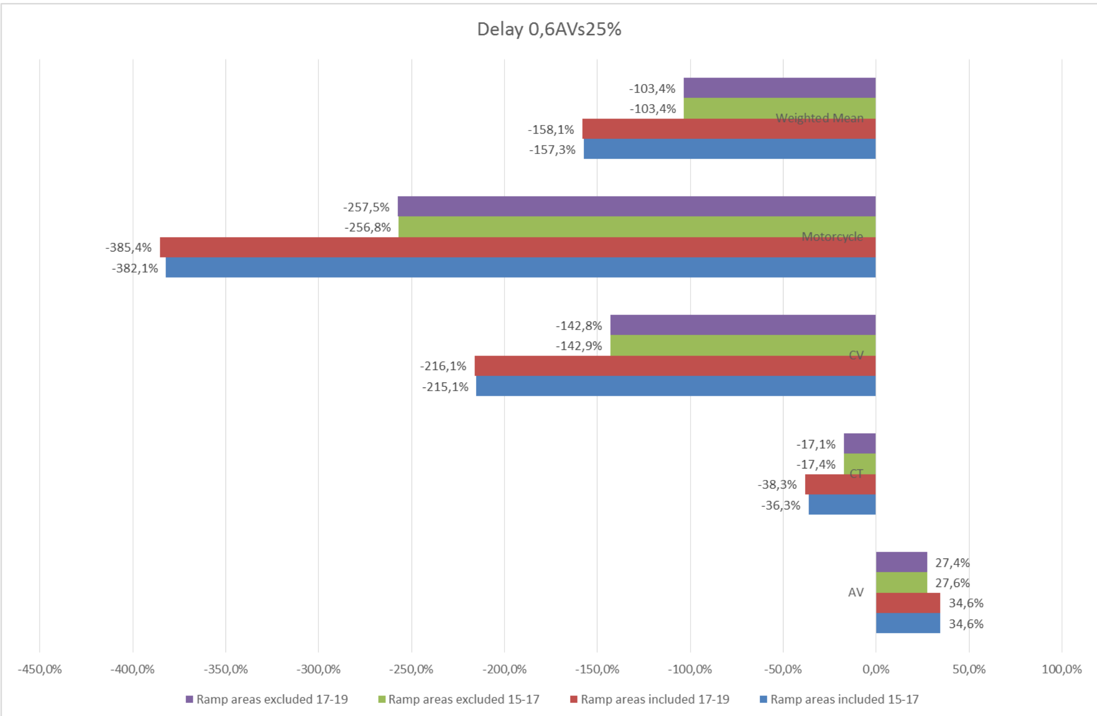
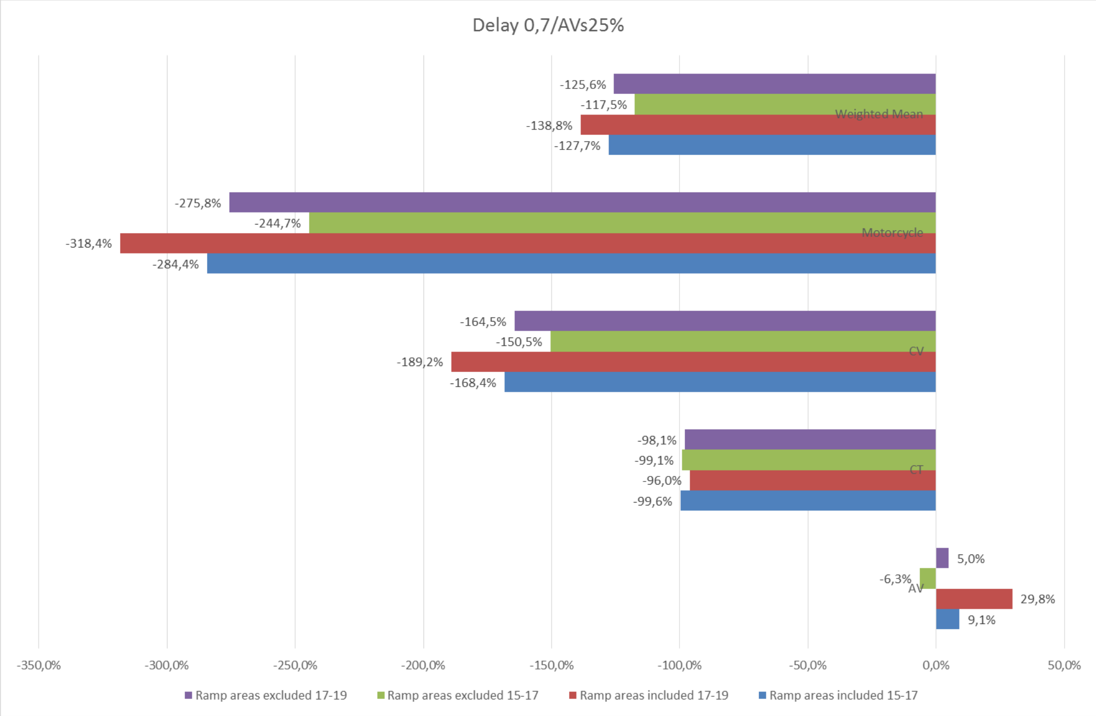
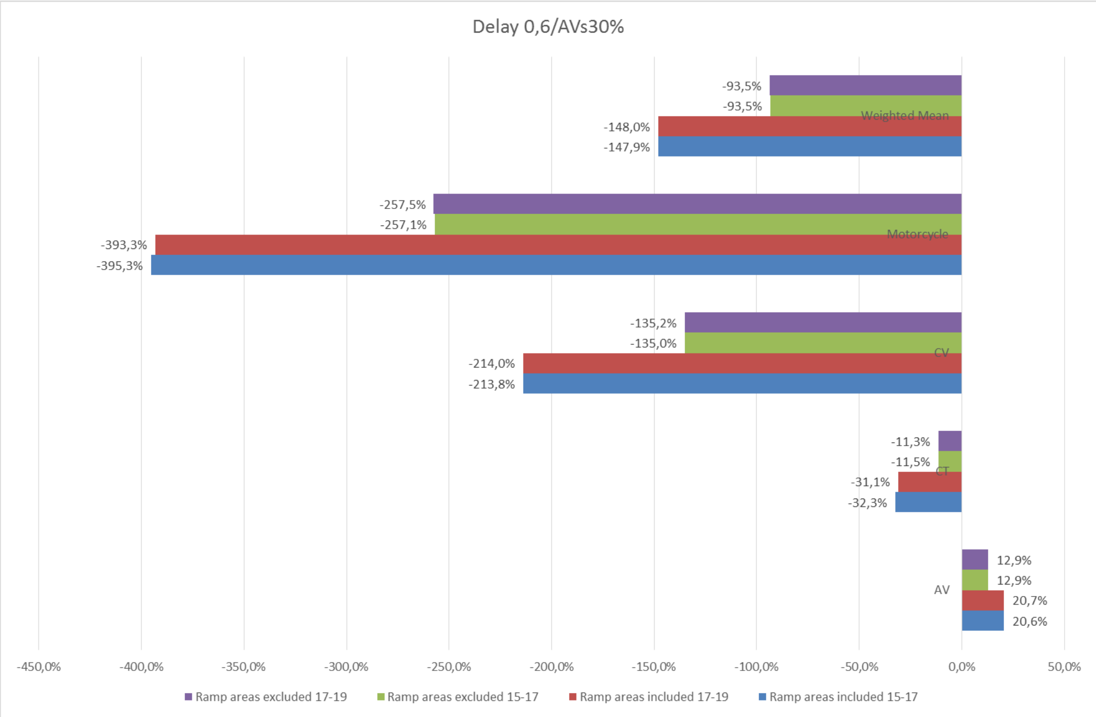


Figure 80. Travel Time in DLA scenario various scalings and penetration rates




Delay 0,7/AVs25%
-125,6%
-117,5%
-138,8%
-127,7%
Weighted Mean
-275,8%
-244,7%
-318,4%
-284,4%
Motorcycle
-164,5%
-150,5%
-189,2%
-168,4%
CV
-98,1%
-99,1%
-96,0%
-99,6%
CT
5,0%
-6,3%
29,8%
9,1%
AV
-350,0% -300,0% -250,0% -200,0% -150,0% -100,0% -50,0% 0,0% 50,0%
Ramp areas excluded 17-19
Ramp areas excluded 15-17
Ramp areas included 17-19
Ramp areas included 15-17


Delay 0,6/AVs30%
-93,5%
-93,5%
-148,0%
-147,9%
Weighted Mean
-257,5%
-257,1%
-393,3%
-395,3%
Motorcycle
-135,2%
-135,0%
-214,0%
-213,8%
CV
-11,3%
-11,5%
-31,1%
-32,3%
CT
12,9%
12,9%
20,7%
20,6%
AV
-450,0% -400,0% -350,0% -300,0% -250,0% -200,0% -150,0% -100,0% -50,0% 0,0% 50,0%
Ramp areas excluded 17-19
Ramp areas excluded 15-17
Ramp areas included 17-19
Ramp areas included 15-17

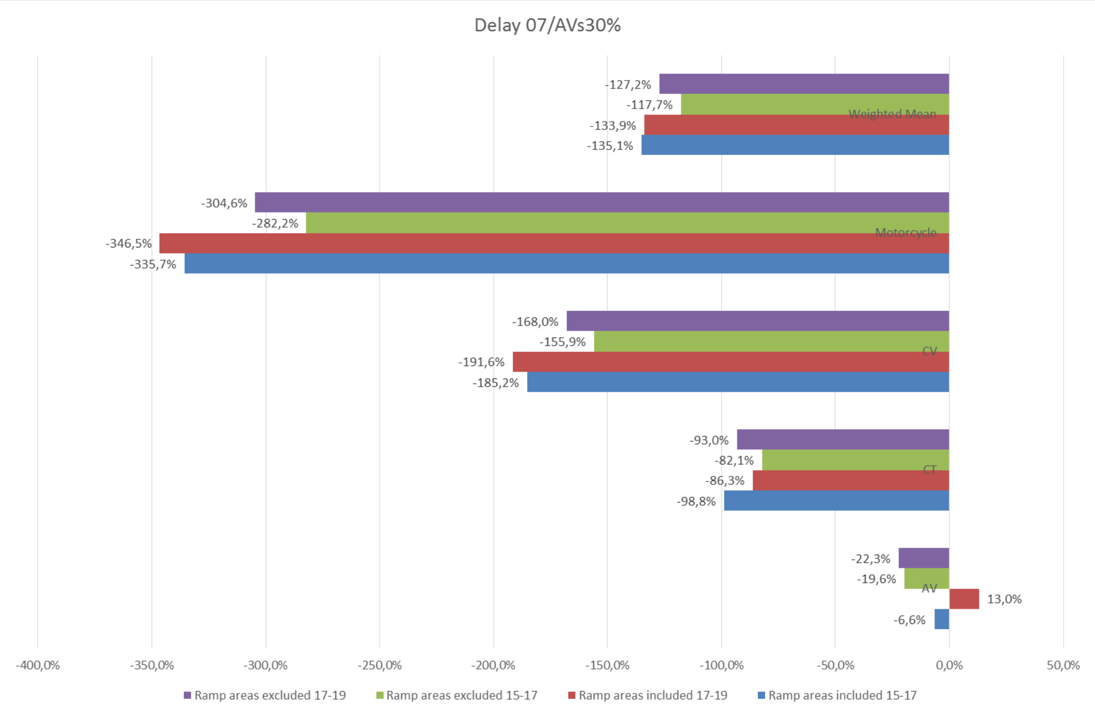
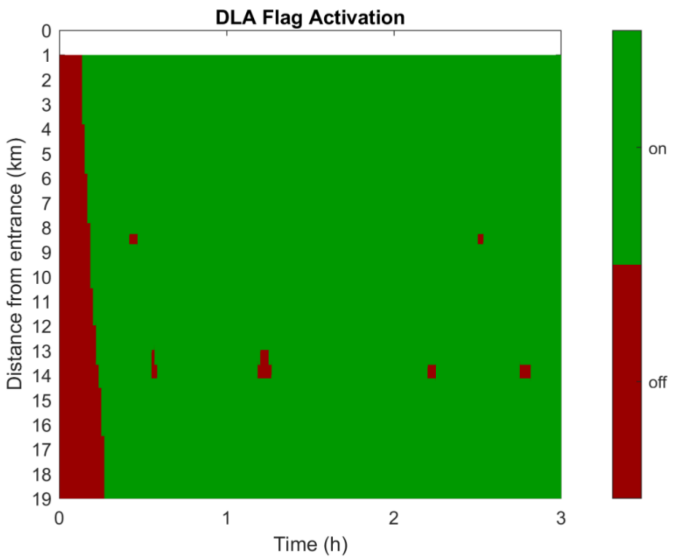
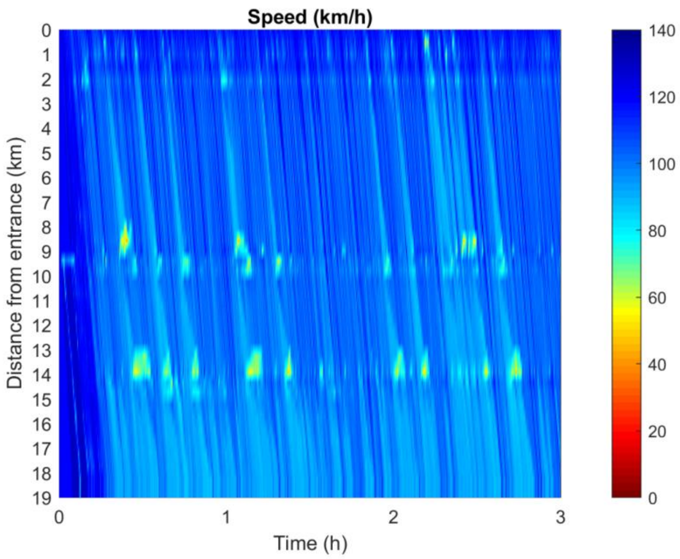


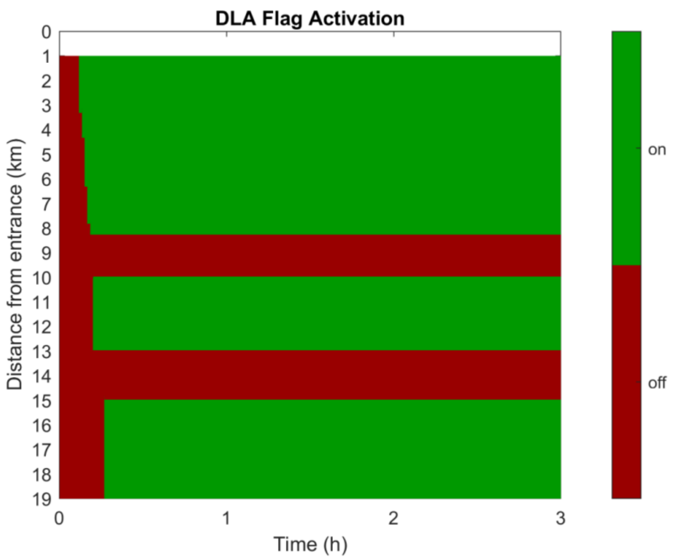
Figure 81. Delay in DLA scenario various scalings and penetration rates

From the results it can be concluded that in most of the simulations the situation is beneficial for AVs, especially when traffic demand is scaled-down to 60% and the penetration of AVs is 25%, but it is not for the rest of the traffic. This leads to a deterioration of the calculated KPIs for the whole population. The results are not really sensitive with respect to the values used for the max thresholds. As expected, whenever areas around sets of on/off-ramps are included in the assignment logic the results are a bit better compared to the opposite case. Of course, this is due to the fact that the lane assigned is always the fast one and inclusion of these areas leads to assignments that continue through the network without interruptions that may lead to more weaving. The DLA controller is able to deactivate these segments on its own based on the density thresholds used.

In the following figure, DLA flag activation and speed plots for traffic demand scaling down to 60% with areas around ramps included in the assignment logic (up) or not (down).


DLA Flag Activation
Distance from entrance (km)
Time (h)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
on
off


Speed (km/h)
Distance from entrance (km)
Time (h)
140
120
100
80
60
40
20
0


DLA Flag Activation
Distance from entrance (km)
Time (h)
on
off

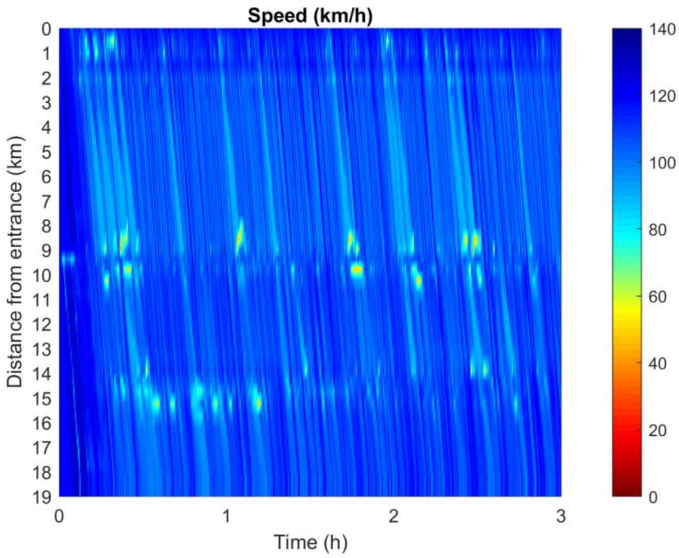


Figure 82. DLA Flag Activation and Speed plots

As mentioned at the beginning of this section, the level of performance of AVs depends on the various settings, e.g. time-gap, maximum acceleration, reaction time, speed limits. On the top, in case of even higher penetration of AVs, one could consider testing the dynamic assignment of 2 lanes. This is expected to improve performance even more because it will allow to the fast AVs to overtake any slow AVs, something that is not possible with just a single lane assigned. However, any improvement on the performance of AVs will not lead to improvements for the rest of the traffic.

7.4 Simulations of a dedicated lane for platooning

Whereas the scenario #1 of INFRAMIX clearly addresses a dedicated lane for private AVs it is worth looking into results using the same simulation framework but assuming that the dedicated lane was reserved for platoons. In the following simulation results on this effort are presented for a simple straight stretch of the motorway with one off and on ramp.

In the following a penetration rate of 20% AVs and 80% conventional cars is assumed. For simplicity reasons no connected cars were assumed in the following simulations.

As an example the three basic destinctons of scenarios on a three lane highway are layed out shortly: platooning on the right, middle and left lane.

7.4.1.Three-truck platooning on the right in combination with high traffic density and high speed limits on the right

<u>Situation:</u> Speed limits have been set to 36.1m/s on all lanes (=130km/h). The traffic density is 5533 fast driving cars and 250 three-truck platoons per hour. Since Lane 0 only has one third of the cars generated on the highway, the time it takes to overtake is drastically increased.

Result: The cars behind the simulated three-truck platoon (pink) are avoiding an overtaking manoeuver since the speed (27m/s = 100km/h) of the column is too much of a risk.

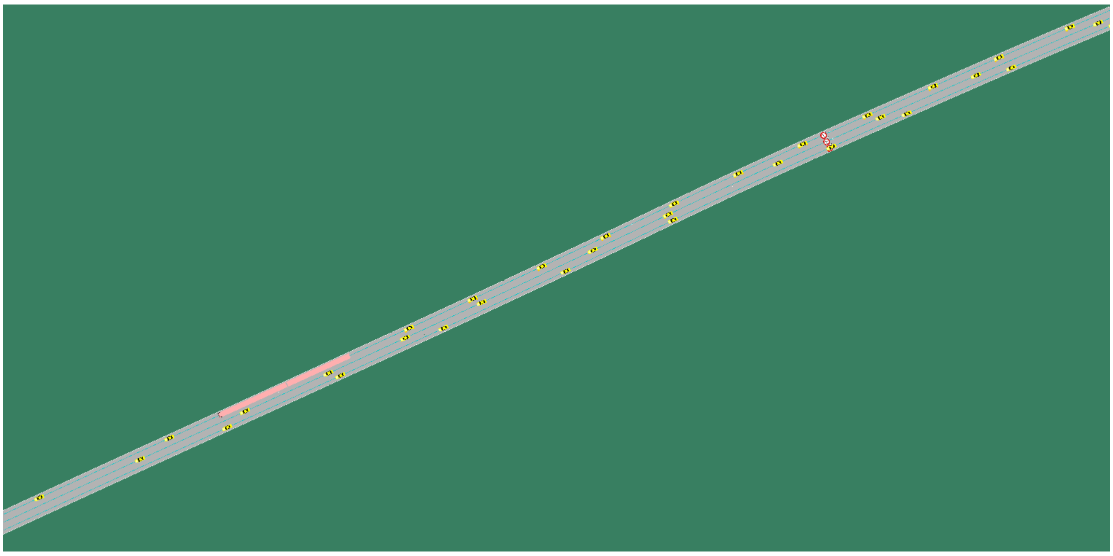


Figure 83. Three-truck platooning on the right in combination with high traffic density and high speed limits on the right

7.4.2Three-truck platooning in the middle in combination with high traffic density and high speed limits

Situation: Speed limits have been set to 36.1m/s on all lanes (=130km/h). The traffic density is 5533 fast driving cars and 250 three-truck platoons per hour. Truck platoons are now driving in the middle lane.

Result: The cars are driving without major disturbance and the traffic flows without problems. Cars are overtaking the fastest on the left lane and cars on the right lane are allowed to overtake the platoon.

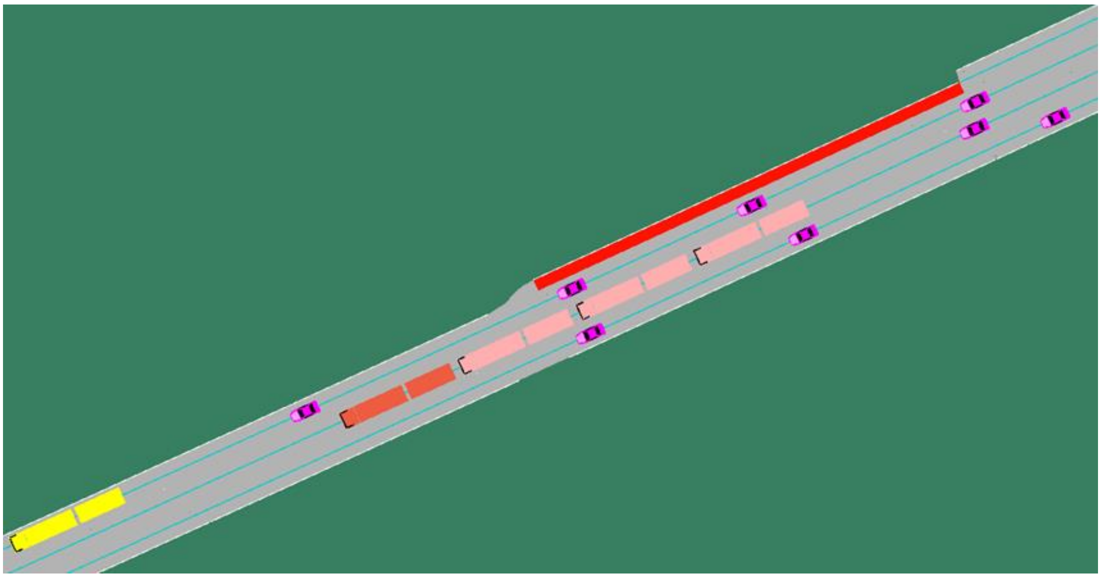


Figure 84. Three-truck platooning in the middle in combination with high traffic density and high speed limits

7.4.3 Three-truck platooning on the left in combination with high traffic density and high speed limits on the left

Situation: Speed limits have been set to 36.1m/s on all lanes (=130km/h). The traffic density is 5533 fast driving cars and 250 three-truck platoons per hour. Truck platoons are now driving on the left lane.

Result: The cars are driving without major disturbance and the traffic flows without problems. Cars are overtaking the fastest on the middle lane and cars on the right lane are all allowed to overtake the platoon.

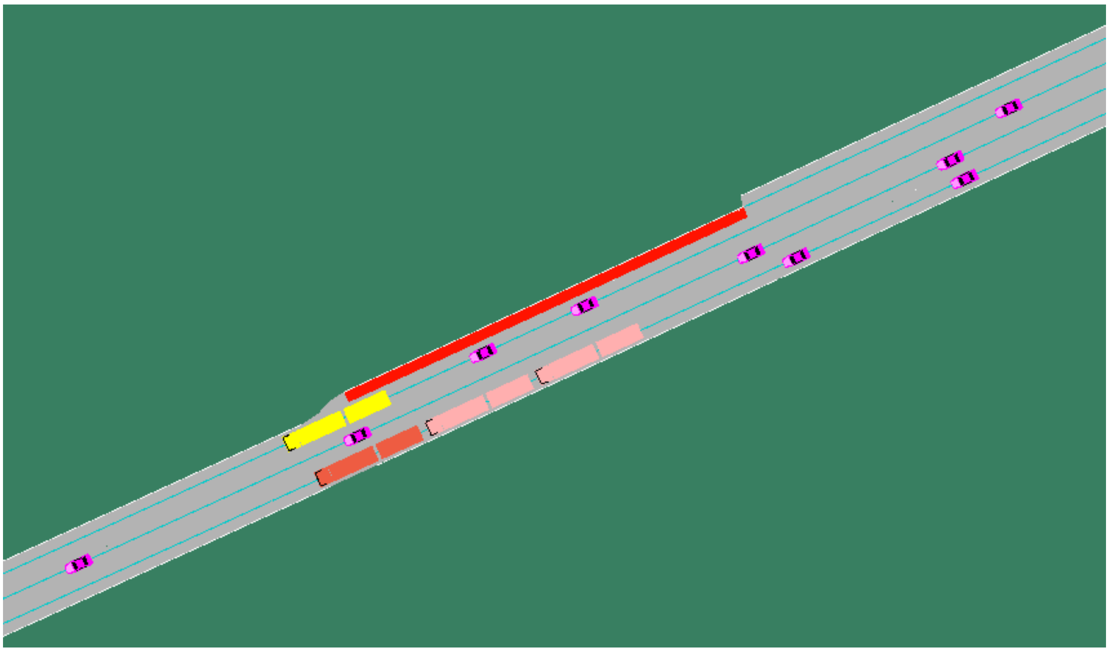


Figure 85. Three-truck platooning on the left in combination with high traffic density and high speed limits on the left

7.4.4 Covered scenarios:

The simulation covered a range of relavant scenarios such as (including the ones described above):

Table 16. Table DLA Platooning Scenarios

scenario	Platooning Lane	Platoon length (nr. Of trucks)	Traffic density	Speed limits	Advices/other
3 lane highway, no ramps	Right	3	5533 fast cars & 250 platoons	130km/h	-
3 lane highway, no ramps	Middle	3	5533 fast cars & 250 platoons	130km/h	-
3 lane highway, no ramps	Left	3	5533 fast cars & 250 platoons	130km/h	-
3 lane highway, no ramps	Right	4	3000 fast cars & 1400 platoons	130km/h	-
3 lane highway, no ramps	Middle	4	3000 fast cars & 1400 platoons	130km/h	-
3 lane highway, no ramps	Left	4	3000 fast cars & 1400 platoons	130km/h	-
3 lane highway	Right	4	3000 fast cars & 1400 platoons	130km/h	On/off Ramp traffic
3 lane highway,	Middle	4	3000 fast cars & 1400 platoons	130km/h	- On/off Ramp traffic
3 lane highway	Left	4	3000 fast cars & 1400 platoons	130km/h	- On/off Ramp traffic
Construction site right	Right	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site right	Middle	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site right	Left	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site right	Right	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance

Construction site right	Middle	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
Construction site right	Left	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
Construction site middle	Right	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site middle	Middle	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site middle	Left	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site middle	Right	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
Construction site middle	Middle	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
Construction site middle	Left	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
Construction site left	Right	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site left	Middle	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site left	Left	4	3000 fast cars & 1400 platoons	130km/h	-
Construction site left	Right	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
Construction site left	Middle	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
Construction site left	Left	4	3000 fast cars & 1400 platoons	130km/h	Lane change 1,3km in advance
3 lane highway	Right	4	3000 fast cars & 1400 platoons	130km/h	trucks on the on ramp

7.4.5 Results of the platooning simulations

Situation: In both simulation runs, the only value that has been modified was the time gap the trucks have. It is clearly visible that the platoons take much less space than the traditional trucks.

Result: Not only can slow cars drive now on the right-most lane, but also faster cars are less likely to be slowed down by these slow driving cars, unable to switch to the right-most lane. Overall, the density of vehicles decreased and the throughput increased which is the optimal case for such an implementation. However, this strong effect is only noticeable if slow cars exist and if they are overtaking trucks. Nevertheless, the number of cars that can drive on the motorway is increased, due to more space.

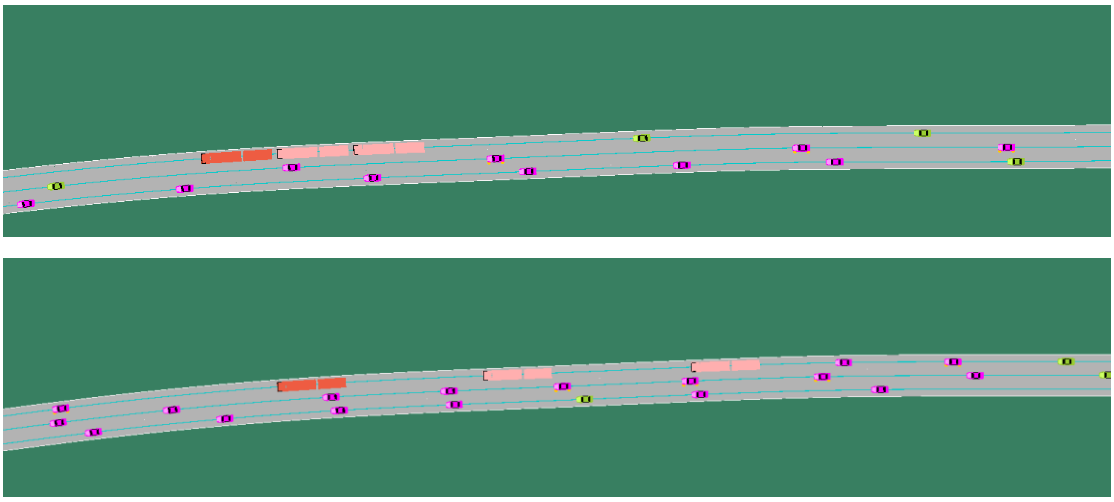


Figure 86. Truck platoon space efficiency

Possibly negatively affected of truck platooning are **lane changing, overtaking and queuing**. Furthermore, it can be broken down to the following points:

vehicles that want to take the off-ramp

- depending on the lane they are driving on(driving on the right disrupts most)
- depending on time gaps and the speed limits(diminishes the accident chance)

vehicles that want to merge, coming from an on-ramp

- depending on the lane they are driving on(driving on the right disrupts most)
- depending on time gaps and the speed limits(diminishes the accident chance)
- depending on ramp metering

vehicles that want to overtake them, or are driving behind

- because overtaking a platoon takes more time and cannot always be done

- because driving on a lane, other than the right would slow down traffic

vehicles close to a construction site

- depending on the lane they are driving on
- depending on the lane that is about to be closed

7.4.5.1 Possible platooning solution

The middle and left-most lane are possible options, but they take a lot of effort to implement. A thinkable option would be truck platoons driving on the right-most lane, on a non-dedicated lane, in controlled and surveilled sections in specific times in specific numbers of trucks.

An important finding is that with platoons, on-ramp scenarios are more likely to result in heavy braking and slow average speeds, especially if trailers on the on-ramp are involved. In general, cars in off-ramp scenarios are driving not so fast and are lining in usually very in advance. Thus, the on-ramp scenarios needs extra attention.

The right-most lane is the most preferable one because driving on other lanes is by far easier to implement however if the density of trucks is high the platoons could easily be transferred to the left lane. In sufficient numbers, this would simulate a road on which the left-most lane has been closed.

The number of trucks should not exceed the length of one half of the minimal off- or on-ramp length they are affecting.

A dedicated lane would only make sense if the number of trucks were so high that vehicles decide to driver on other lanes in advance. If trucks only make up a minor portion of the vehicles on their lane, a dedicated lane would lead to traffic jams.

If the weather or other factors would increase the chance of an accident, platooning would also have to be abandoned.

Preferably platooning should take place on motorway routes in times where vehicles from off- and on-ramps are not disturbed eg. not too many are driving on them. An easy implementation would be in areas where already many trucks are driving.

A further important finding is, that the merging success from the on ramp onto a platooning lane on the right seems to be very much dependend on the starting (spawning) time of the vehicles on the on ramp. This means that merge success can be drastically increased when the vehicles on the on ramp are released with respect to gaps in the platoons, a strategy commonly known as ramp metering.

7.5 Communication Flow

The communication flow of the demonstration runs has been as described in INFRAMIX deliverable D3.1 – "Design and development of infrastructure elements".

Therefore, the INFRAMIX Management Center (IMC) has been established and applied as core element for the dissemination process. This process covered the operating of the digital hybrid communication by using two different communication technologies – the ITS-G5 channel as well as the Cellular network link. Additionally, for the Spanish demonstration run, a communication between the IMC and the Traffic Management Center has been applied in order to test the centralized activation of digital road signs.

The major part of the demonstrated communication-flow focused on the digital hybrid communication link, as illustrated in Figure 87. This implies the ITS-G5 air link, including the communication flow from the IMC to ITS-G5 Road Side Units as well as also the Cellular air link, including the communication flow from the IMC to the Cellular Service Provider, which further disseminates the digital messages to its connected services. While the INFRAMIX Scenarios 1 and 2 got fully covered by this communication chain, Use-Case 3 of Scenario 3 got realized by dedicated triggers of the Cellular Service Provider.

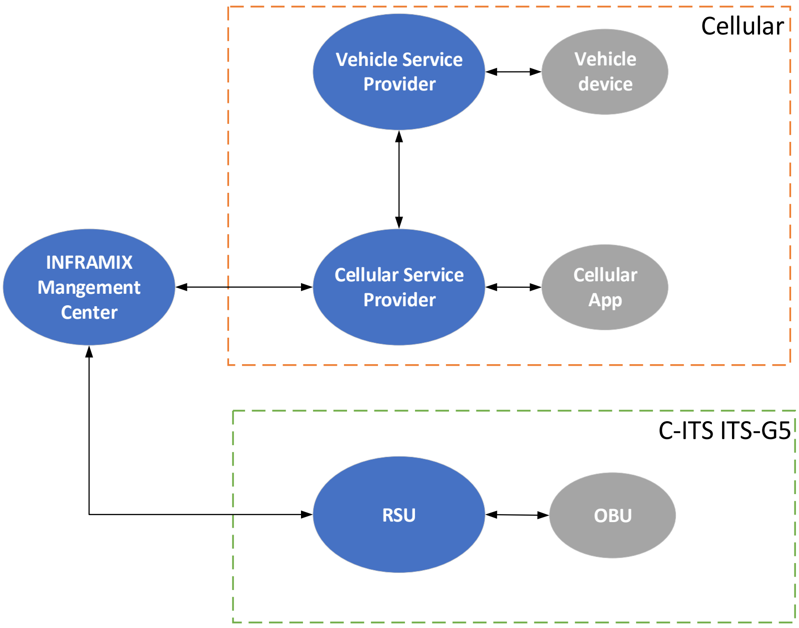


Figure 87. Digital hybrid communication flow

The communication flow from the INFRAMIX Management Center to the Cellular Service Provider as well as to the Road Side Unit has been performed in real-time. This included in total, for both test-sites and for all performed INFRAMIX scenarios, an amount of 78 unique C-ITS messages, which has been prepared as mockups. Each C-ITS message has been allocated to respective INFRAMIX scenarios and sub use-cases, based on its unique content.

The dissemination process of the messages has been initiated by the IMC to both communication channels by providing the corresponding C-ITS messages to each API. Further, the IMC has performed a message update to each API by a frequency rate of 3 seconds, which provided the possibility to update or cancel the C-ITS message transmission. Other frequency-rates (lower rates of 1sec; 2sec as well as higher rates of 5sec; 10sec) has successfully been tested as well during the preparations of the demonstration runs.

ITS-G5 communication channel

The ITS-G5 communication flow has been initiated by the IMC and in further consequence fulfilled by the corresponding C-ITS Road Side Units. This processed included the transmission of the relevant C-ITS messages from the IMC to the RSUs. This has been realized by a OCIT-C communication link, including an XML-encoded messages. The ITS-G5 RSU further broadcasted the received ITS-message over the ITS-G5 air-link to passing (ITS-G5) connected vehicles with a frequency-rate of 10Hz.

The demonstration runs included standardized C-ITS message-types as well as new, not yet standardized, C-ITS message-type enhancements.

Following message-types has been part of the INFRAMIX demonstration runs

- Decentralized Environmental Notification Messages (DENM), for:
    - Short-Term Road Work Warning
    - Hazardous Weather Warnings

- enhanced In-Vehicle Information (IVI), for:
    - Dedicated Lane assignment for AVs
    - Traffic Regulations (e.g. Speed limit)
    - Traffic Recommendations (e.g. Gap advices)
    - Road Work Warnings

The focus of the demonstration run in Spain was on specific scenarios and use-cases per timeslot, resulting in operating of one, max. two, RSUs at the same time via the IMC. On the contrary, the demonstration run in Austria was set up by having different scenarios & use-cases on different locations along the test-site. This included a total amount of 12 RSUs which has been operated via the INFRAMIX Management Center during one timeslot.

In conclusion, dedicated message-transmissions as well as the communication flow of a long-term demonstration run with several different message-sets has been performed and successfully been proofed.

Cellular Communication Channel

The cellular communication chain, from the IMC to the Service provider to the end user, was implemented as described in detail in D 3.2 and D 3.3 and tested on the Spanish and Austrian test site.

The main focus of the cellular test was on the Spanish test site where scenarios 1, 2 and 3 where tested during different laps on four days. For the tests of scenario 1 and scenario 2 broadcast messages (messages addressing all traffic participants) were necessary. In these cases, the IMC sent broadcast advices and restrictions in Datex II format to the service provider. The service provider encoded the data and made the messages available to the OEM and the Application in the format specified in D 3.2, via an API. The connection between the IMC and the Service provider and the service provider and the APP and the OEM backend worked flawless throughout the test. The update frequency of the Application was set to one request in 3 seconds.

For the test of scenario 3 use case 3, unicast messages where necessary. For these tests only, the Service provider and the OEM where planned to be active. The unicast messages where generated and pulled by the OEM backend. However, during the tests the connection from the OEM backend to the vehicle failed and scenario 3 could not be tested as planned. To test scenario 3, the app was extended on site to showcase scenario 3 use cases 1 and 3. As a result all scenarios could be tested using the cellular communication link.

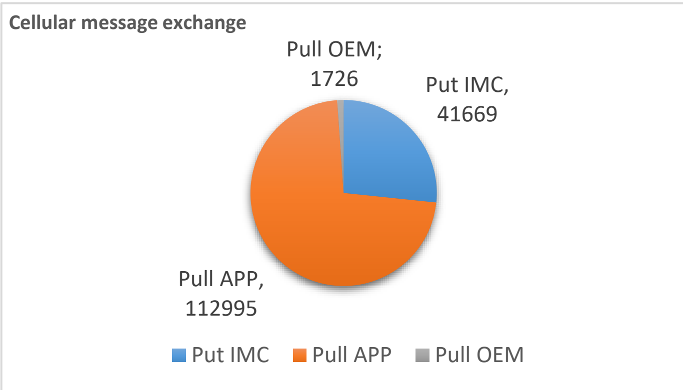


Figure 88. Diagram of exchanged messages. A total of 156390 messages were exchanged via the API of the cellular service providers. 113.137 of these messages were pull requests from the App and the OEM and 41669 put messages from the IMC.

During the tests in Spain and Austria a total of more than 156.390 messages were exchanged via the API of the cellular service provider, as shown in Figure 88**Error! Reference source not found.** From these 41.669 put advices from the IMC and 114.721 pull requests from the Application and the OEM backend. While the application requested with a high frequency (3 seconds) leading to 112.995 requests the OEM requests where adjusted to the test site and scenario messages leading to 1.726 requests during the tests.

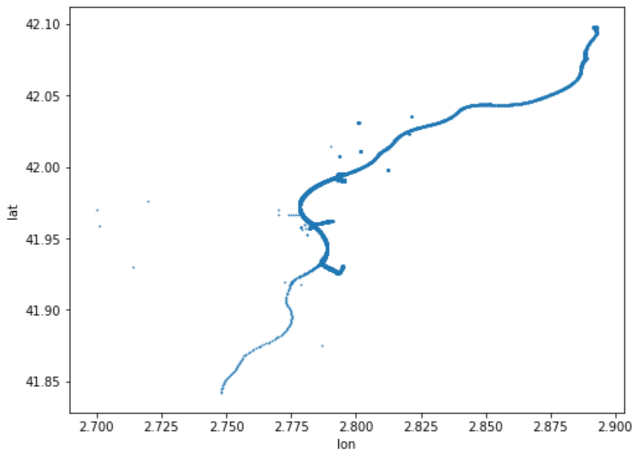


Figure 89. Spatial distribution of requests during the tests in Girona. X- and Y-axes show longitude and latitude of the requests (blue dot), respectively.

In Figure 89, the requests are spread along the whole Spanish test site, reflecting the high request frequency of 3 seconds of the cellular devices during the tests.

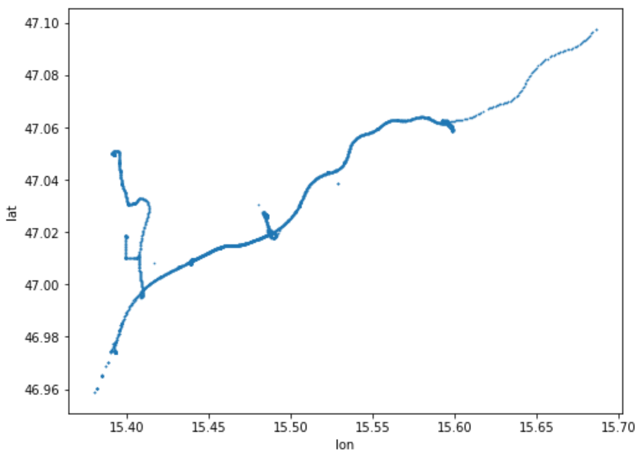


Figure 90. Spatial distribution of requests on the Austrian test site. X- and Y-axes show longitude and latitude of the requests (blue dot), respectively

In Figure 90 the requests are spread along the whole Austrian test site, reflecting the high request frequency of 3 seconds of the cellular devices during the tests.

The service provider received the requests from devices on both test sites. The requests are equally distributed over the whole test track reflecting the high request rate of the cellular devices.

In summary, the cellular communication link could be used to test all scenarios, demonstrating the feasibility of the proposed communication link for future use in advanced traffic management for conventional and automated vehicles.

7.6 Results from Hybrid Testing

Hybrid Testing is a novel testing methodology based on the ICOS co-simulation platform [2], [3] which was implemented and extended in the scope of the INFRAMIX project to test several mixed traffic scenarios involving autonomous and manual driven vehicles. A detailed description of the Hybrid Testing concept as well as a test site description can be found in Deliverable 4.1 *INFRAMIX plan for systems interaction, integration and testing*. This current deliverable includes the results and a detailed discussion of the collected data during the Hybrid Testing campaign, which took place in October 2019 to demonstrate the end results as well as to log data for further analysis together with partners.

In the developed Hybrid Testing solution, a real-life automated test vehicle is driven on an enclosed proving ground, whereas the necessary inputs required by the perception sensors are provided by a real time co-simulation of static and dynamic environments using SUMO traffic simulation software. The utilized automated driving function is an in-house developed SAE Level- 3 ADAS function called *Motorway Chauffeur*. More details about the *Motorway Chauffeur* and its functionalities can be found in Deliverable 2.3 *Specification of sub-microscopic modelling for intelligent vehicle behavior*.

A number of use case studies were conducted during the development Hybrid Testing experiments as well as a number of key performance indicators were evaluated in a post processing process. The following sections include a specification of all measured or calculated key performance indicators which can be found in Deliverable 5.1 *Plan for evaluation and users' engagement*, a detailed description of all conducted use case studies as well as a result discussion of all studies.

7.6.1 Description of the evaluation parameters (KPIs)

The following Table 18 contains all the key performance indicators that are evaluated during hybrid testing experiments as well as description of the corresponding indicators.

Table 17. Description of evaluation parameters (KPIs)

Scenario / Testday / Testrun	Identifier of the testrun Testday 1: the 3rd of October 2019 Testday 2: the 22nd of October 2019
Vehicle has merged	If the vehicle was able to merge into the traffic on the main road
Vehicle has stopped	If the vehicle has stopped at the end of the onramp
Distance to merge (begin)	Distance from the start position to the beginning of the lane change manoeuvre
Distance to merge (end)	Distance from the start position of the VuT[2] to the end of the lane change manoeuvre

[2] VuT … Vehicle under Test

min Time gap	Minimum time gap between the VuT and the nearest target vehicle. Noted N/A[3] if there are no target vehicles present in the scenario
min Distance gap	Minimum distance gap between the VuT and the nearest target vehicle. Noted N/A if there were no target vehicles present in the scenario
Min TTC	Minimum TCC (Time to collision), Noted N/A if there are no target vehicles present or the TTC is not defined, e.g. if the front vehicle is faster
IVI send	The RSU sends the IVI – yes/no/emulated
IVI received	The OBU sends the IVI – yes/no/emulated
IVI Speed	Recommended speed, send out via the IVI
Vehicle has adapted the speed	If the VuT has increased the speed according to the recommend speed of the IVI
Mean speed ego	Mean speed of the VuT without acceleration and braking phase
Mean speed ego in relevance zone	Mean speed of the VuT inside the relevance zone defined in the IVI
Mean speed all	Mean speed of all existing vehicles including the VuT in the test scenario

***Remark-1* (Calculation of the start and end of a lane change)**:

We define the 10% and 90% lateral distance thresholds (also known as the rise-time) of the y-offsets between the centrelines of the two lanes corresponding to the lane change manoeuvre, and fit a line tangent to the intercept on the common road marking between the two centrelines. The lane change manoeuvre beginning instant at 0% (t_{begin}) and the end instant at 100 % (t_{end}) are indicated in Figure 91. These time points are used to calculate the distance to merge.

[3] N/A … not applicable

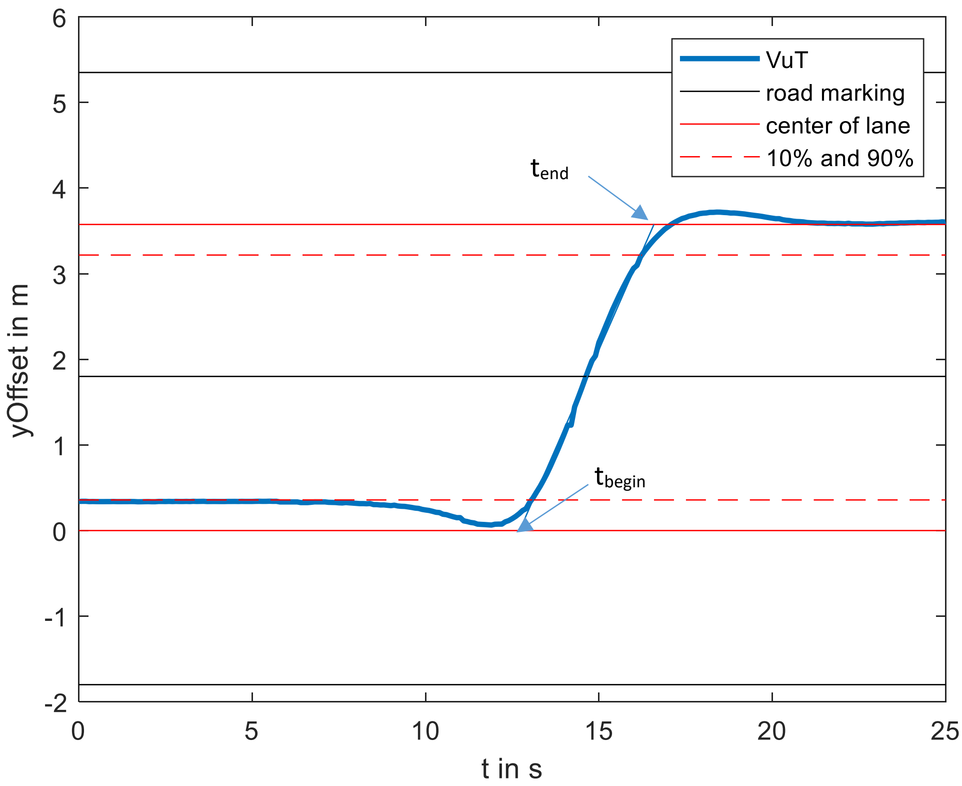


Figure 91. Lane change maneuver and the related definitions

Remark-2 (Time gap):

The time gap is defined and is relevant for two cases:

1. if a vehicle is driving along the same lane with the VuT, and
2. In case of a lane change manoeuvre where a vehicle is driving along on the target lane.

In the first case above the time gap can be defined and evaluated at all times, possibly for both the nearest vehicle in front and the nearest vehicle behind the VuT. In the second case, the time gap can be described with reference to the beginning and end of the lane change manoeuvre.

Remark-3 (Distance gap):

The distance gap is only relevant with respect to a vehicle on the same lane or with respect to a vehicle on the target lane during a lane change manoeuvre. Here it is assumed that the distance gap is evaluated from the beginning of the lane change manoeuvre possibly for both of the nearest vehicle in front and to the nearest vehicle behind the VuT.

Remark-4 (TTC):

$$TTC = \begin{cases} TTC = \dfrac{x_{target} - x_{ego} - l}{v_{ego} - v_{target}} \ldots v_{ego} > v_{target} \\ not\ defined \ldots v_{ego} \geq v_{target} \end{cases}$$

In the definition according to the above formula, "*ego*" vehicle (i.e., the VuT) is assumed to be behind of the "*target*" vehicle in front. x_{ego} and x_{target} are respective positions of the vehicles, and l is the vehicle length in meters. Also, v_{ego} and v_{target} are the respective longitudinal velocities of the corresponding vehicles.

7.6.2 Experiment Stack I – Lane Change & Merging

This Experiment Stack contains the Scenario 1 to 3. These scenarios model an automated vehicle driving on an onramp situation and where the automated vehicle tries to merge into the traffic on the main road. The Vehicle under Test (VuT) starts from standstill (0 km/h initial velocity) at the rightmost lane, which represents the road on-ramp

Table 18. Experiment Stack-I KPIs

Scenario /Testday /Testrun	Vehicle has merged	Vehicle has stopped	Distance to merge (begin)	Distance to merge (end)	min Time gap	min Distance gap	min TTC
-	-	-	m	m	s	m	s
1/1/1	Yes	No	28.90	64.3	N/A	N/A	N/A
1/2/1	Yes	No	26.30	63.1	N/A	N/A	N/A
2/1/1	Accident	No	25.40	N/A	0	0	0
2/2/1	Accident	No	25.10	N/A	0	0	0
2/2/2	Yes	No	35.90	70.7	1.31	11.85	N/A
2/2/3	Yes	No	27.70	63.7	1.52	13.3	N/A
2/2/4	Yes	No	15.80	56.9	0.4	3.69	1.11
3/1/1	No	Yes	N/A	N/A	N/A	N/A	N/A
3/2/1	No	Yes	N/A	N/A	N/A	N/A	N/A
3/2/2	No	Yes	N/A	N/A	N/A	N/A	N/A

7.6.2.1 Analysis & Discussion of the Scenarios

Scenario 1:

After the vehicle starts from standstill along the on-ramp, it tries to accelerate to 30 km/h utilizing its ACC controller. At a speed of 20 km/h, the vehicle is permitted to initiate a lane change manoeuvre to merge into the main lanes (represented by lane two and three from the right). Since there is no traffic hindering the VuT from changing the lane, neither the time- and distance-gap nor the TTC is calculated (marked yellow in Table 8). Since the main road narrows to a single lane at the end of the test track due to the bottleneck, the VuT performs another lane change.

Scenario 2:

Figure 92 below illustrates Scenario 2 at the starting point. The VuT is depicted by the solid red rectangle and is surrounded by three target vehicles (depicted with empty red rectangles) in its vicinity. The VuT accelerates to the desired speed and merges into the traffic on the main road. This experiment is similar to the previous one, but the VuT must take into account the behaviour of the surrounding vehicles when performing a lane change. The blue line in Figure 92 represents the trajectory that is followed by the VuT in this scenario.

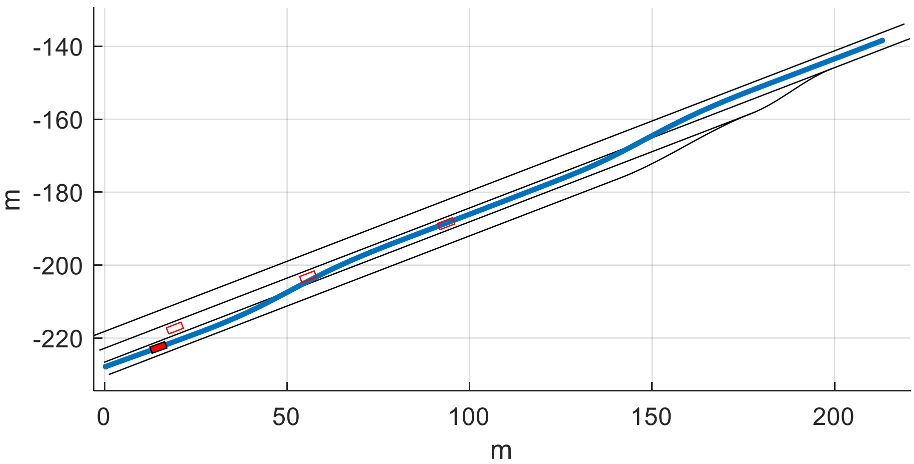


Figure 92. Vehicle positions in experiment 2/2/2

In the two test runs (2/1/1 and 2/2/1) the VuT ended up in a collision with one of the simulated vehicles of the virtual traffic due to a suspected error in the trajectory planner (marked green in Table 19). The trajectory planner was not able to notice that there were vehicles on the left lane. In these two cases the time- and distance-gap as well as the TTC parameters were recorded as zero.

In the test runs 2/2/2, 2/2/3 and 2/2/4 the VuT merged correctly into the traffic on the main road.

Since, the TTC is only defined when the following vehicle is faster than the leading vehicle the TTC for the test run 2/2/2 and 2/2/3, it was not possible to evaluate the TTC for the respective test runs marked blue in Table 19.

Scenario 3:

In all the corresponding test runs of the Scenario 3 the VuT was not able to find a sufficient gap on the main road to merge and eventually stopped at the end of the onramp. Due to the dense traffic modelled, this behaviour was expected. For this reason, no merge distances and time gaps could be calculated (marked purple in Table 19).

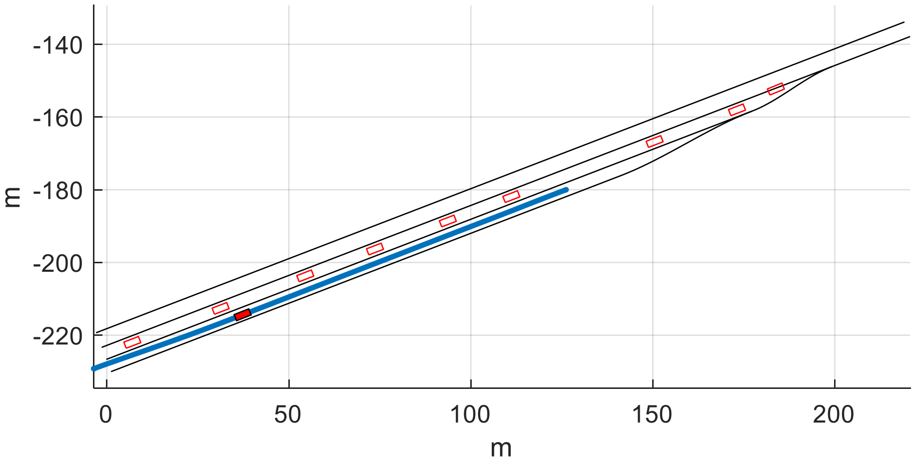


Figure 93. Vehicle positions in experiment 3/1/1

7.6.3 Experiment Stack II – Emulated IVI-Message

Experiment Stack II represents the behaviour of an automated vehicle while it is driving on the main road with other simulated vehicles and reacts to the emulated (i.e., software defined) IVI messages. The initiation of lane changes are the result of the road layout as well as the traffic situation. In all following scenarios the VuT starts on the second lane (from the right), which represents the first lane of the main road.

Table 19. Experiment Stack II KPIs

Scenario /Testday /Testruns	IVI send	IVI received	IVI Speed	Vehicle has adapted the speed	mean Speed ego	mean speed ego in relevance zone	mean speed all	min dist gap	min time gap	min TTC
-	-	-	km/h	-	km/h	km/h	km/h	m	s	S
4/1/1	no	no	N/A	no	30.8	30.2	30.8	N/A	N/A	N/A
5/1/1	emulated	emulated	40	yes	34.3	37.5	34.3	N/A	N/A	N/A
6/1/1	emulated	emulated	40	no	32.1	32.7	29.5	7.63	0.85	4.64
7/1/1	emulated	emulated	40	no	23	23.2	20.1	3.46	0.6	7.41

7.6.3.1 Analysis & Discussion of the Scenarios

<u>Scenario 4:</u>

This scenario depicts a baseline situation without any IVI messages. The VuT drives on the main road accelerates to 30 km/h and changes the lane before the lane ends. Since there are no other vehicles present, time- and distance-gap as well as TTC were not calculated (marked yellow in Table 20).

Scenario 5:

This scenario shows that the VuT is capable to react accordingly to a speed recommendation when the VuT is driving on the main road and performing a lane change. The VuT drives with a speed of 30km/h on the main road when it receives an IVI message with a speed recommendation of 40 km/h and the corresponding coordinates of the relevance zone. As expected, the VuT adapts the speed to the recommended IVI speed.

Scenario 6:

Scenario 6 shows that the VuT can also react to an IVI message when traffic is present in the near vicinity (Figure 94). The VuT is driving with 30km/h on the main road when receiving an IVI message. Now a leading vehicle hinders the VuT from reaching the recommended speed since it drives slower. The VuT is not able to reach the recommended speed of 40 km/h but it adapts it´s speed to the leading vehicle (marked green in Table 20).

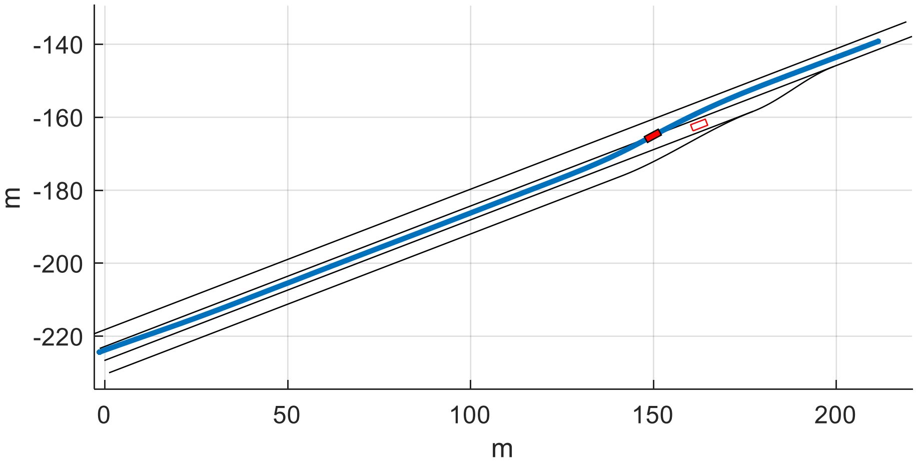


Figure 94. Vehicle positions in experiment 6/1/1

Scenario 7:

While the VuT is driving on the main road with a speed of 30km/h it receives an IVI message with a speed recommendation of 40 km/h in the relevance zone. Since there are a number of slower vehicles (Figure 95) on both lanes, the VuT is not able to follow the advice (marked green in Table 20) and adapts its behaviour to the traffic situation.

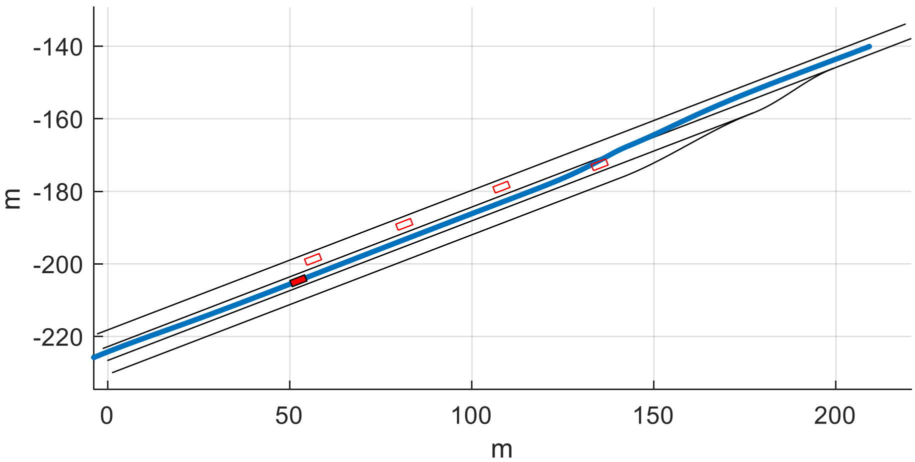


Figure 95. Vehicle positions in experiment 7/1/1

7.6.4 Experiment Stack III – Full Communication Chain

Scenarios 4 to 7 are the same as in in the case with the emulated IVI-Message. The only difference is that the IVI is sent by a real RSU and received by an OBU inside the vehicle. This extension of the previous scenarios depicts the full communication chain.

Table 20. Experiment Stack III KPIs

Scenario /Testday /Testrun	IVI send	IVI received	IVI Speed	Vehicle has adapted the speed	mean Speed ego	mean speed ego in relevance zone	mean speed all	min dist gap	min time gap	min TTC
-	-	-	km/h	-	km/h	km/h	km/h	m	s	S
4/2/1	no	no	N/A	no	30.7	30.1	30.7	N/A	N/A	N/A
5/2/1	yes	yes	40	yes	34.5	37.7	34.5	N/A	N/A	N/A
5/2/2	yes	yes	50	yes	36.4	41.9	36.4	N/A	N/A	N/A
6/2/1	yes	yes	50	no	34.2	36.1	29.7	11.7	1.17	4.85
6/2/2	yes	yes	50	no	34.2	36.3	29.4	13.82	1.33	5.2
7/2/1	yes	yes	50	no	28.3	27.1	25.1	2.04	0.4	1.36
7/2/2	yes	yes	50	no	23	23.4	19.1	3.34	0.5	3.46

7.6.5 Analysis & Discussion of the Hybrid Testing Results

In this chapter we described the analysis of the real life testing results from Hybrid testing. When analysed from the overall perspective, particularly comparing Table 20 and Table 21 the results are nearly the same as expected. In some scenarios the recommended speed was changed from 40km/h to 50 km/h (marked blue in Table 21) and the results show that the vehicle is also capable of following this recommendation. As in previous results the distance- and time-gap as well as the TTC is not applicable when no leading vehicle is present (marked yellow in Table 21). The VuT was not able to adapt its speed accordingly to the recommended speed when it was hindered by surrounding traffic (marked green in Table 21).

The particular outcomes of the study can be listed as follows:

- Successful and repeatable real-world proof of concept Hybrid Testing experiments are achievable on a proving ground, which in this case was the ÖAMTC Lang/Lebring proving ground near Graz.
- Scenarios involving the interaction of VuT with new road control elements (e.g., ITS-G5, 4G/5G and/or VMS) and traffic management centers can be setup an evaluated.

- Testing and evaluations of ADAS functions running on the VuT in mixed traffic scenarios involving simulated automated and conventional vehicle traffic can be performed.

The presented implementation of Hybrid Testing can be extended in various ways. First of all, in this proof-of-concept implementation only a traffic simulator was utilized for the scenario modeling, which as a first step, can be improved by the integration of a photo-realistic environment simulator (such as CARLA, Unity 3D, LG Simulator, etc.) to the co-simulation framework. In doing so, it can be possible to include physical sensor models to the co-simulation framework for use with perception algorithm development.

7.7 Results from Submicroscopic Simulation Analysis

This section summarizes the results from the use case studies of submicroscopic simulations. A detailed description of these scenarios can be found in section 3.2. The main focus in the current section is to analyse the specific KPIs which are defined for each use case to so observe the effects of measures on the respective KPIs that are relevant for the evaluation of safety and efficiency."

7.7.1 Results and KPI analysis – Bottleneck – On ramp

Traffic flow

The following tables show the results of the flow measurements for the baseline as well as for both measure simulations. The flow is measured with detectors at the beginning of segment 3 see Figure 7 in 3.2.1. These detectors count all passing vehicles from second 300 to 360. The total number of vehicles per hour is derived by extrapolation for one hour. A comparison of the mean flow value with the actual flow value in Table 22 based on ASF Data in 3.2.1 shows that mainly level of services with high traffic densities exhibit high standard deviations.

Table 21. Bottleneck Onramp - Traffic flow estimated - Baseline

SC3UC3, Bottleneck, Onramp, Baseline				
Flow [veh/h]	**LOS A**	**LOS B**	**LOS C**	**LOS E**
Mean	1603	3051	4397	4952
Std	110	266	415	506
Min	1290	2190	2850	3300
Max	1890	3540	5160	6000

Table 22. Bottleneck Onramp -Traffic flow estimated - Measure with Speed Advice

SC3UC3, Bottleneck, Onramp, Measure: Speed Advice				
Flow [veh/h]	LOS A	LOS B	LOS C	LOS E
Mean	1612	3059	4414	5008
Std	103.6	235.2	393.9	493.6
Min	1290	2520	3090	3360
Max	1890	3570	4980	6090

Table 23. Bottleneck Onramp -Traffic flow estimated - Measure with Speed + Lane Change Advice

SC3UC3, Bottleneck, Onramp, Measure: Lane Change Advice				
Flow [veh/h]	LOS A	LOS B	LOS C	LOS E
Mean	1609	3053	4368	4735
Std	110.4	259.5	358.9	388.8
Min	1290	2190	3420	3420
Max	1920	3600	4980	5310

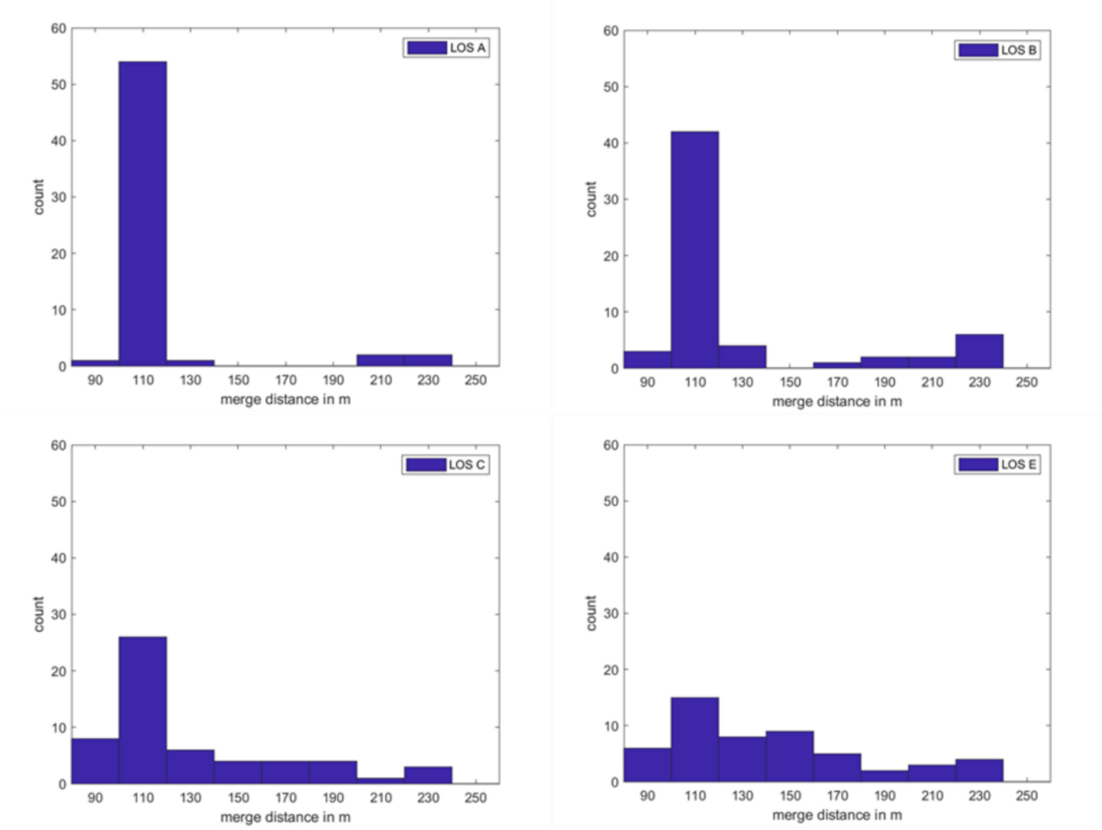
Distance to merge

The distance to merge is measured starting from that point where the acceleration lane meets the main road til the end of the lane change manoeuver.

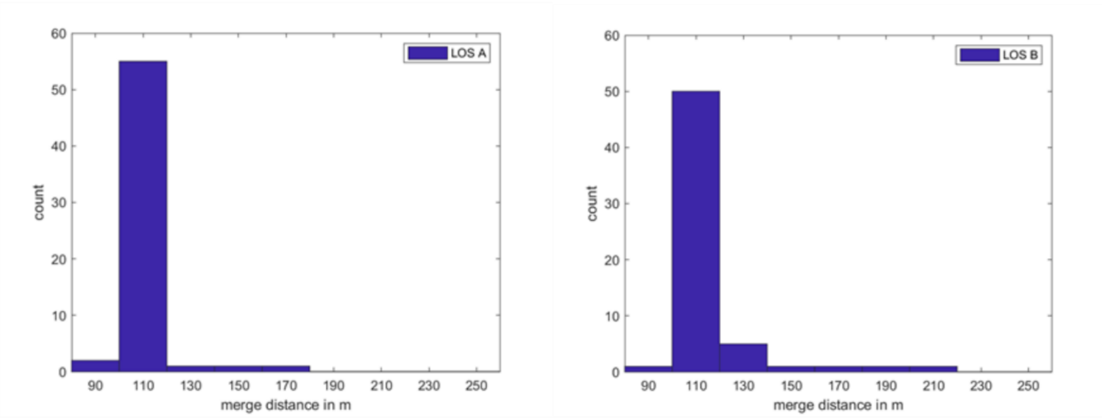
The results from the baseline simulation are summarized in Table 25. It can be seen that a lot of distances to merge are centered around 110 meters in LOS A. This is obvious because the traffic flow here is extremely low and the ego vehicle takes the chance to merge into the main traffic as soon as possible. As is to be expected, the merge distances are distributed nearly over the whole length of the acceleration stretch with increasing traffic flow. For instance, the maximum merge distance in LOS E is about 238 meters. As the traffic density is high in LOS E it becomes more difficult and takes longer times for the automated ego vehicle to find a convenient gap.

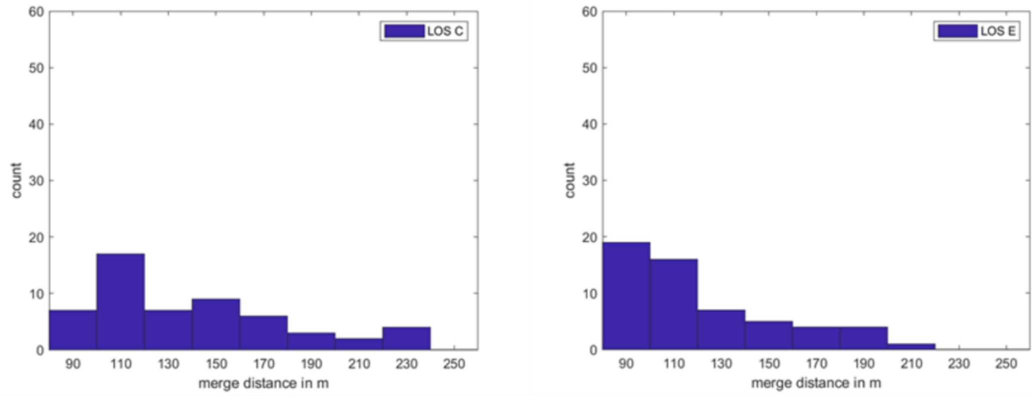
Table 24. Bottleneck Onramp – Merge Distance - Baseline

SC3UC3, Bottleneck, Onramp, Baseline				
Merge Distance [m]	LOS A	LOS B	LOS C	LOS E
Mean	113.4	127.2	127.3	138.4
Std	28.3	43.3	39.2	42.2
Min	96.9	97.8	76.9	76.5
Max	227.5	235.8	232	238.3



A comparison of the baseline simulation with the first measure simulation (Table 26), including speed advices, shows only small changes of the merge distance dispersion in LOS C and LOS D. More effects can be observed in LOS E when comparing the baseline simulation with the second measure simulation (Table 27).





It seems that the speed advice in combination with the lane change advice has significant effects on the merge distances. The combination of both messages causes shorten merge distances in LOS E.

Table 25. Bottleneck Onramp -Merge Distance - Measure Speed Advice

SC3UC3, Bottleneck, Onramp, Measure: Speed Advise				
Merge Distance [m]	**LOS A**	**LOS B**	**LOS C**	**LOS E**
Mean	112.1	124.6	133.7	138.4
Std	25.5	41.1	43.1	42.2
Min	96.9	91.9	76.9	76.5
Max	229.7	235.4	235.1	238.3

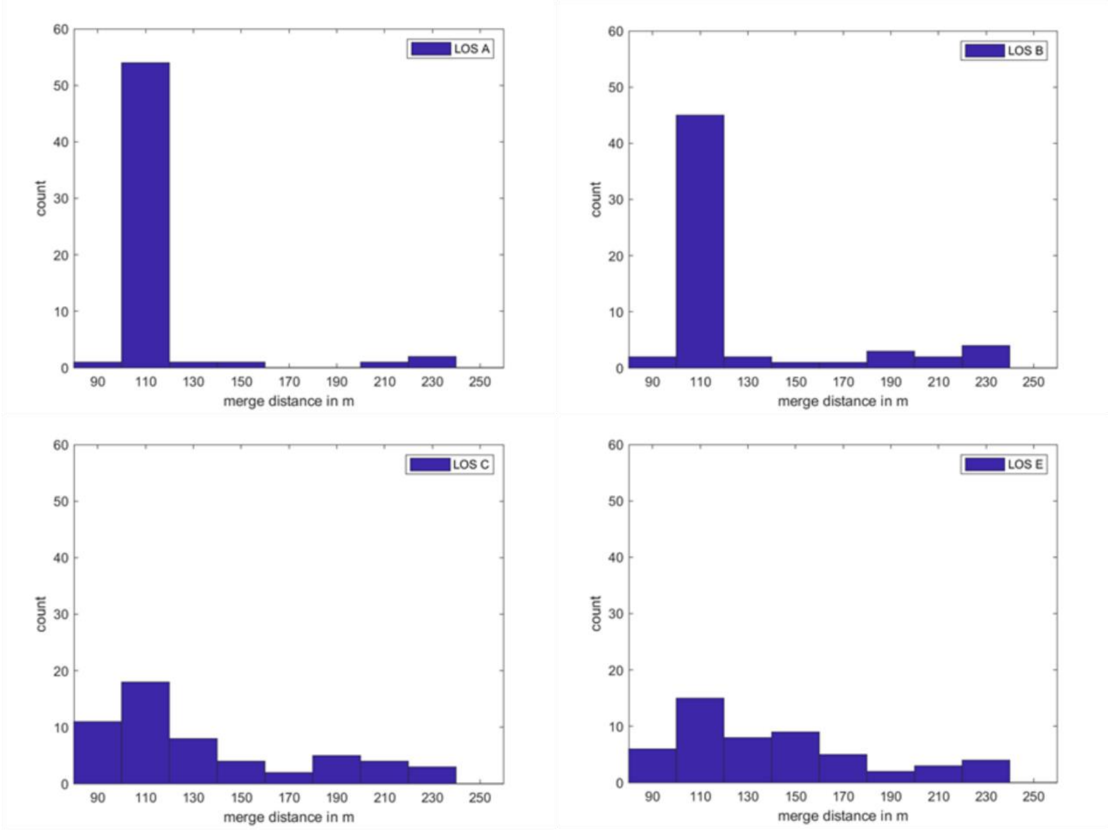
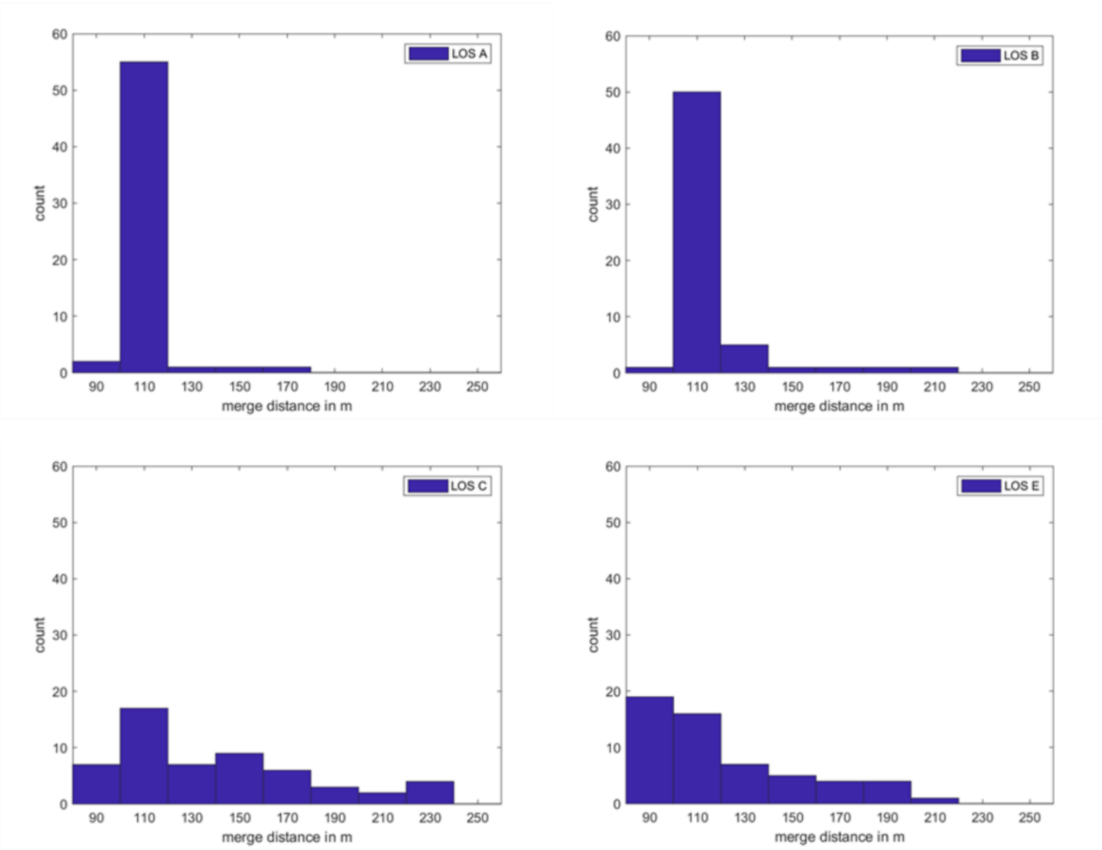


Table 26. Bottleneck Onramp -Merge Distance - Measure Speed + Lane Change Advice

SC3UC3, Bottleneck, Onramp, Measure: Speed and Lane Change Advise				
Merge Distance [m]	LOS A	LOS B	LOS C	LOS E
Mean	107.8	112.8	137	117.9
Std	10.9	21.2	42.2	33.9
Min	95.5	97.5	80	77.1
Max	172.9	215.8	238.6	207.4



<u>Number of experiments – number of successful merges</u>

Figure 96 shows the total number of experiments (red bar) versus the number of successful merges (green bars) of the ego vehicle when it drives along the onramp and tries to merge into the traffic on the main road. Since Figure 96 is only a graphical representation, the exact number of stops of VuT can be found in Table 28. In LOS A and LOS B the VuT was able to merge into the main traffic in every experiment. In LOS C three respectivly four experiments leaded to unwanted stops at the end of the manoever zone. Furthermore, we can observe in the baseline simulation of LOS E that the VuT stopped seven times. The same behaviour can be observed in the first measure scenario, which means that this measure does not show an improvement. But the second measure scenario shows that the speed advice in combination with the lane change advice has a positive effect because here we can count only two stops of the VuT.

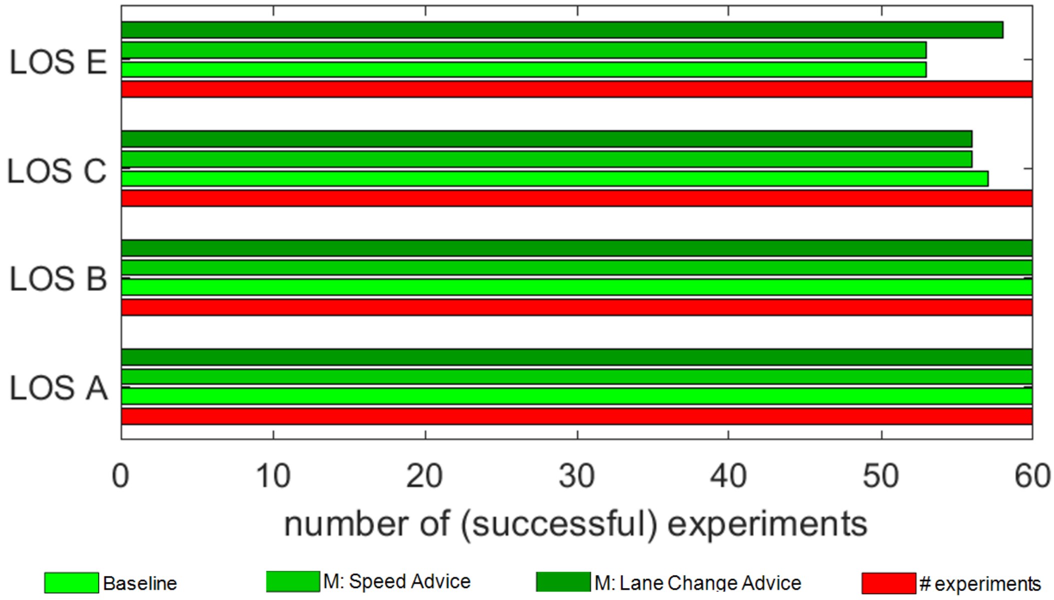


Figure 96. Bottleneck Onramp - Number experiments versus number merges

Number of stops

Table 28 shows the number of stops of the diverent vehicle classes at the merging zone of the onramp. There are only stops of the VuT at the end of the onramp in higher traffic densities.

Table 27. Bottleneck Onramp - Number of Stops

		Baseline Number of Stops	Measure I Number of Stops	Measure II Number of Stops
LOS A	CarICOS	0	0	0
LOS B	CarICOS	0	0	0
LOS C	CarICOS	3	4	4
LOS E	CarICOS	7	7	2

Mean Speed

The mean speed is calculated only in segment 3 of the test site of every vehicle class. The mean speed here is the harmonic mean speed also called space-mean speed [7]. Beside the mean speed value, the following tables 29-31 include the standard deviation as well as the maximum speed.

The maximum speed is 130 km/h for the baseline whereby in measure I & II the maximum speed is slightly smaller than 130km/h because of the reduced speed segment 3. The deviation of the mean speed from the maximum speed arise because single vehicle classes are subject to certain distributions. Additionally, the mean speed decreases with higher traffic densities since the vehicles influence each other with increasing level of service.

Table 28. Bottleneck Onramp - Mean Speed - Baseline

Traffic Density	Vehicle Type	Mean Speed km/h	Deviation km/h	Maximum Speed km/h
LOS A	Conventional	110.03	3.82	130
	Automated	88.97	4.31	130
	Motorcycle	98.31	11.06	129.78
	Truck	86.95	1.69	87.84
	Trailer	80.19	0.99	80.64
LOS B	Conventional	101.61	6.26	130
	Automated	85.54	4.4	120.85
	Motorcycle	94.63	9.46	129.82
	Truck	83.46	3.66	87.84
	Trailer	77.7	3.84	80.64
LOS C	Conventional	94.17	5.37	130
	Automated	82.62	4.34	128.02
	Motorcycle	91.31	7.58	130
	Truck	78.94	5.93	87.84

	Trailer	75.48	5.25	80.64
LOS E	Conventional	88.34	6.21	130
	Automated	79.65	4.87	122.15
	Motorcycle	84.05	8.43	121
	Truck	74.07	6.8	87.84
	Trailer	71.49	6.71	80.64

Table 29. Bottleneck Onramp - Mean Speed – Measure Speed Advice

Traffic	Vehicle Type	Mean Speed km/h	Deviation km/h	Maximum Speed km/h
LOS A	Conventional	98.62	1.5	128.63
	Automated	88.37	4.12	118.58
	Motorcycle	93.36	6.24	111.74
	Truck	86.55	3	87.84
	Trailer	80.09	1.22	80.64
LOS B	Conventional	96.33	3.17	128.52
	Automated	84.94	3.78	109.22
	Motorcycle	90.51	6.93	118.51
	Truck	83.31	3.8	87.84
	Trailer	77.68	3.56	80.64
LOS C	Conventional	91.95	4.08	128.7
	Automated	82.32	4.41	109.48
	Motorcycle	90.65	4.87	103.64
	Truck	77.9	6.31	87.84
	Trailer	74.85	5.87	80.64
LOS E	Conventional	86.77	5.69	109.58
	Automated	79.63	4.54	107.82
	Motorcycle	82.91	6.17	100.01
	Truck	73.52	6.72	87.84
	Trailer	71.55	6.27	80.64

Table 30. Bottleneck Onramp - Mean Speed – Measure Speed + Lane Change Advice

Traffic	Vehicle Type	Mean Speed km/h	Deviation km/h	Maximum Speed km/h
LOS A	Conventional	96.32	3.05	128.56
	Automated	88.63	4.85	129.96
	Motorcycle	92.54	6.3	111.74
	Truck	86.05	3.33	87.84
	Trailer	79.9	1.38	80.64
LOS B	Conventional	87.11	7.85	126.32
	Automated	81.68	7.3	121.61
	Motorcycle	84.63	9.63	116.53
	Truck	80.85	5.4	87.84

	Trailer	77.05	4.39	80.64
LOS C	Conventional	70.61	8.37	122.26
	Automated	68.55	7.5	108.72
	Motorcycle	71.64	8.4	100.8
	Truck	69.5	7.07	87.84
	Trailer	70.6	6.13	80.64
LOS E	Conventional	62.04	7.44	113.33
	Automated	61.25	6.29	102.49
	Motorcycle	63.48	7.43	100.01
	Truck	64.85	6.02	87.84
	Trailer	65.69	5.19	80.64

In what follows, Figure 97 to Figure 99, illustrate partial results of the previous tables which are also discussed in detail below.

Figure 97 presents the mean speed of conventional vehicles for the baseline as well as the measure simulations. The mean speed is plotted against the flow. We can see that an increasing flow entails a decreasing mean speed. The decrease is different for baseline and infrastructure measures. Especially in case of the lane change advice (yellow line) the second and third lanes get more crowed because the automated vehicles are forced to leave the rightmost lane, and this effects the mean speed.

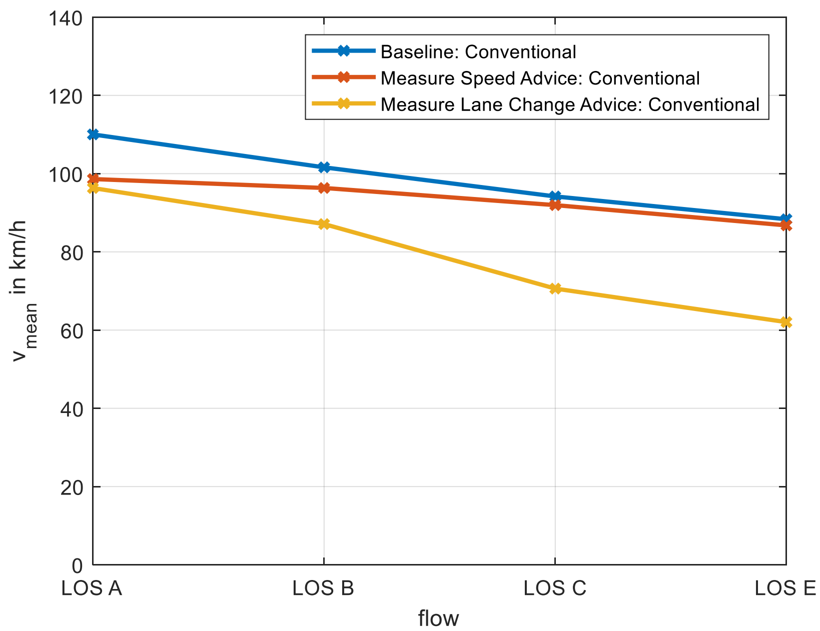


Figure 97. Bottleneck Onramp – Mean Speed – Conventional

Figure 98 shows the mean speed of automated vehicles. There are slightly differences between the baseline (blue line) and the speed advice (red line), because the mean speed of automated vehicles is already below the speed advice. But the same effect as for conventional vehicles leads to low mean speeds of automated vehicles in case of the lane change advice (yellow line).

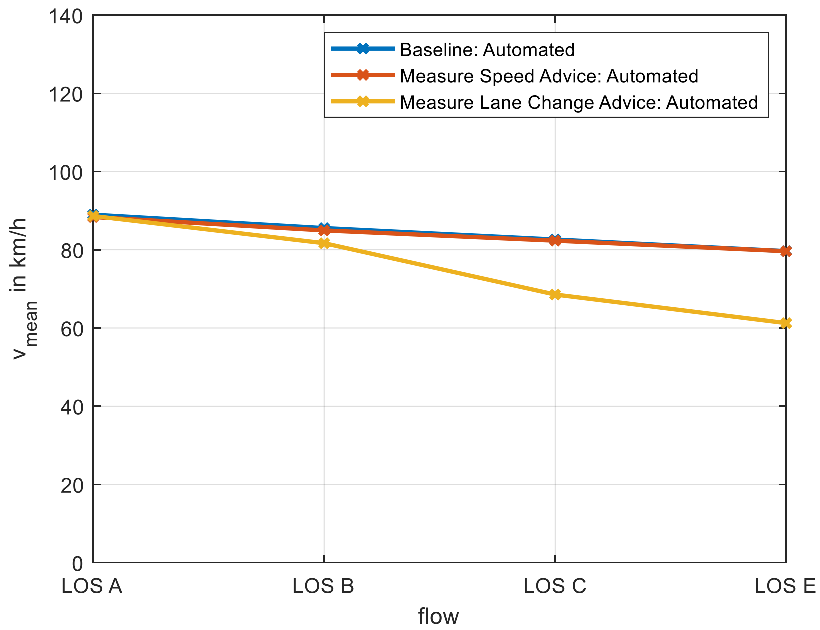


Figure 98. Bottleneck Onramp – Mean Speed – Automated

In Figure 99, the mean speed of trucks and trailers are visible. Again, there is small difference between baseline (blue line) and measure one (red line), because the mean speed is below the speed recommendation. But we can also see a minor effect on measure two (yellow line) at higher traffic volumes (LOS C and LOS E).

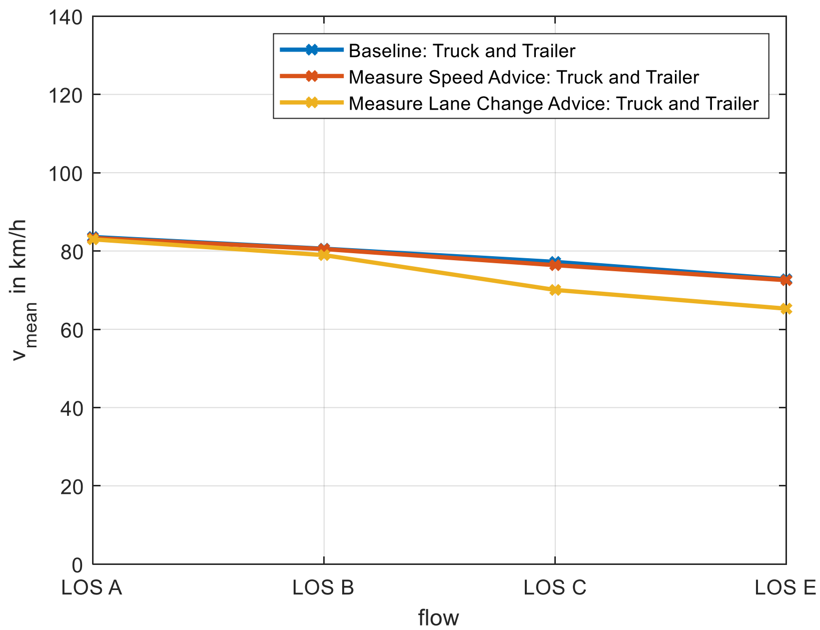


Figure 99. Bottleneck Onramp – Mean Speed – Truck and Trailer

Travel time

Table 32 lists the mean travel time and its deviation for all simulations, level of services and vehicle types. The mean traveltime was calculated of all vehicle classes as long as they drive in segment 3.

Table 31. Bottleneck Onramp - Travel time

		Baseline		Measure I		Measure II	
		Mean s	Deviation s	Mean s	Deviation s	Mean s	Deviation s
LOS A	Conventional	31.47	0.93	35.1	0.43	36.07	1.12
	Automated	38.61	1.95	38.85	1.88	38.91	2.51
	Motorcycle	34.56	3.36	36.65	2.12	37.15	2.6
	Truck	40.44	1.66	40.69	1.78	40.8	1.62
	Trailer	43.32	0.68	43.39	0.8	43.46	0.81
LOS B	Conventional	33.83	1.41	35.85	0.94	39.1	3.41
	Automated	39.66	1.44	39.91	1.59	41.57	3.39
	Motorcycle	36.65	3.84	38.07	3.3	41.03	5.47
	Truck	41.07	1.68	41.19	2.13	42.35	2.79
	Trailer	43.98	1.52	44.04	1.57	44.55	2.38
LOS C	Conventional	36.73	1.68	37.46	1.23	47.96	4.93
	Automated	40.97	1.39	41.05	1.42	49.2	4.51
	Motorcycle	38.31	2.5	38.72	1.95	47.26	4.84
	Truck	43.23	2.67	43.75	3.25	48.71	4.08
	Trailer	45.62	3.14	45.98	3.48	48.25	3.5
LOS E	Conventional	38.61	2.29	39.34	2.09	51.85	4.65
	Automated	42.06	1.83	42.24	1.97	52.6	4.17
	Motorcycle	40.16	2.83	40.52	2.61	51.76	4.77
	Truck	45.79	3.98	46.1	4.58	50.69	3.74
	Trailer	48.06	4.75	48.12	4.74	50.98	3.11

Figures 100-102 show a comparison of the mean travel time for conventional, automated vehicles as well as Trucks and Trailer in all three simulations. Figure 100 depicts the mean traveltime of conventional vehicles during the baseline simulation as well as both measure simulations. It can be seen that the lowest mean traveltime of conventional vehicles is during the baseline simulation. Since speed advices are included in both measure simulations it is expected that the traveltime will increase in section 3. When comparing the measure simulations we can see that the mean traveltime even increases in measure II.

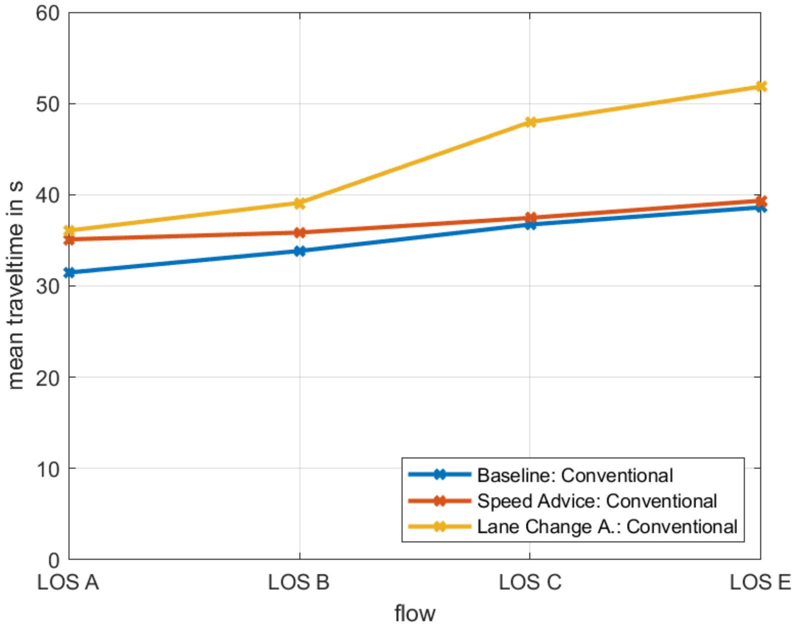


Figure 100. Bottleneck Onramp -Mean travel time of conventional vehicles in baseline. measure I and measure II simulation

In Figure 101 the mean travel time of automated vehicles during the baseline simulation as well as both measure simulations can be seen. When comparing the baseline simulation with the measure simulation of all level of services we can see that the speed advice does not have a significant impact on the traveltime. However, the measure simulation II delivers increasing traveltimes with increasing traffic flow.

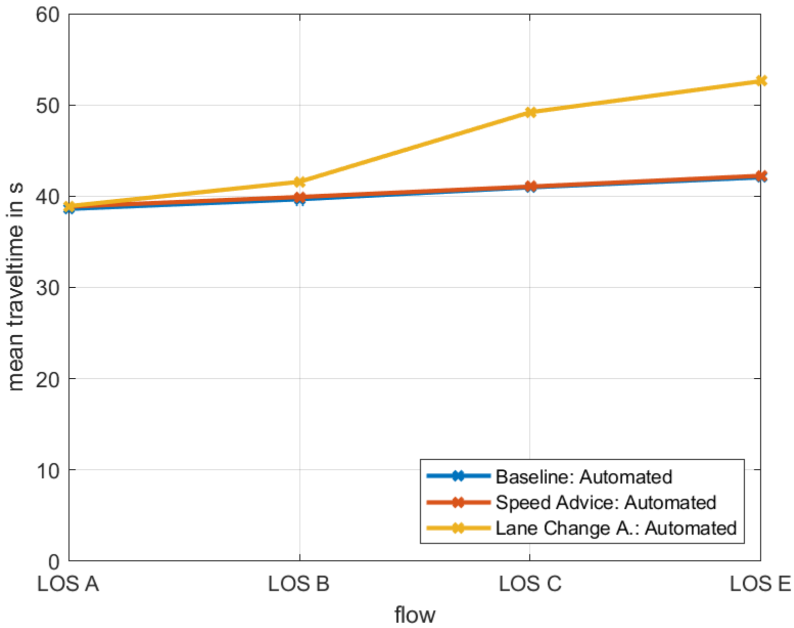


Figure 101. I Bottleneck Onramp -Mean travel time of automated vehicles in baseline. measure I and measure II simulation

In Figure 102 the travel time of trucks and trailers are summarized overall level of services as well as baseline and measure simulations. Due to low differences between the initial speed of trucks and trailers and the speed advice in segment 3 the mean travel time of trucks and trailers does not change in large extensions neither in measure simulations nor with increasing traffic flow.

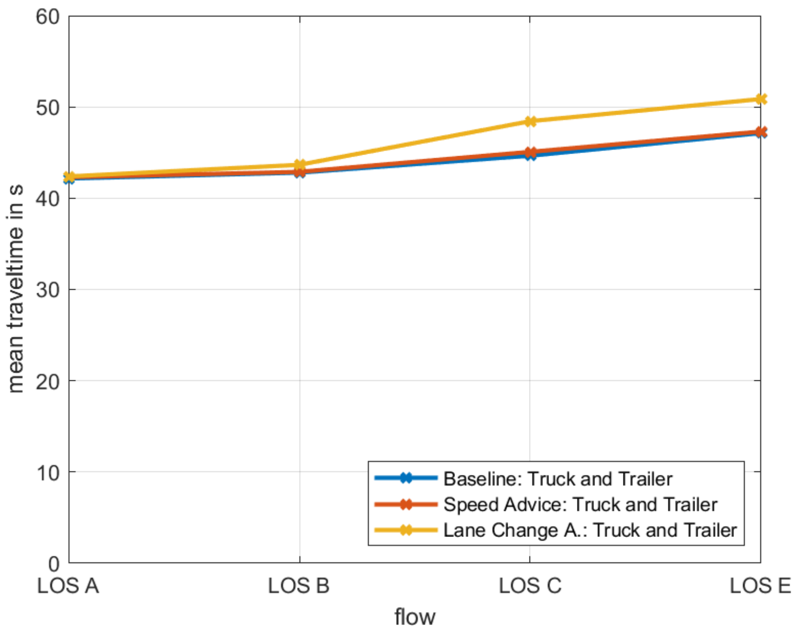


Figure 102. Bottleneck Onramp -Mean travel time of trucks & trailers in baseline. measure I and measure II simulation

Inter vehicle gap on rightmost lane

This KPI is a cumulative measure of the distances between vehicles on the rightmost lane of the main road, which quantifies the condition whether a vehicle from the onramp can merge into the main traffic or not. This measure indirectly indicates how hard it is for an automated vehicle to find a suitable gap for merging.

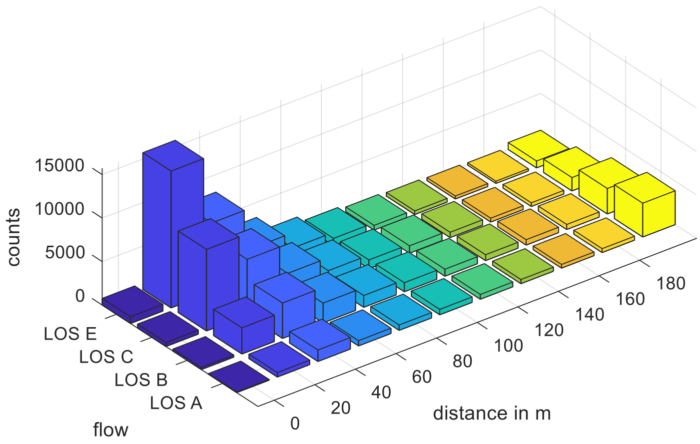


Figure 103. Bottleneck Onramp -Inter vehicle gap on rightmost lane - Baseline simulation

We analysed this KPI for varying traffic densities. With reference to **Error! Reference source not found.** which shows the baseline simulations, we observe for LOS A that there are not many gaps lower than 200m. This value can also be interpreted as that there is no vehicle on the observed part of the main road. As a result, the VuT is not hindered by any car when merging. With higher traffic flow the number of smaller inter vehicle gaps is naturally increasing, and this makes the finding of a proper gap for the VuT more challenging. This is also observed in the Figure 103 with increasing traffic densities.

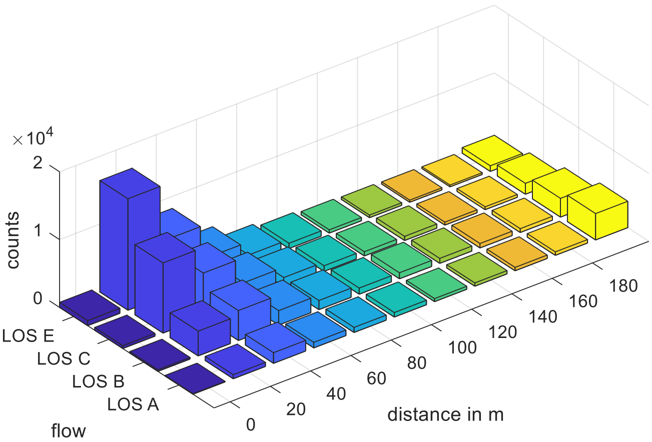


Figure 104. Bottleneck Onramp -Inter vehicle gap on rightmost lane - Measure simulation I (Speed Advice)

In Figure 104 inter vehicle gap on right most lane for the measure simulation with speed advice is shown. Here the variation of the counts is very similar to that of the baseline simulations except that the cumulative counts with increasing traffic density is more than that of the baseline simulations. This indicates that for denser traffic, a persistent recommendation for lower speed (100 km/h) will reduce the overall inter-vehicle gaps, which is in acordance with the expectations.

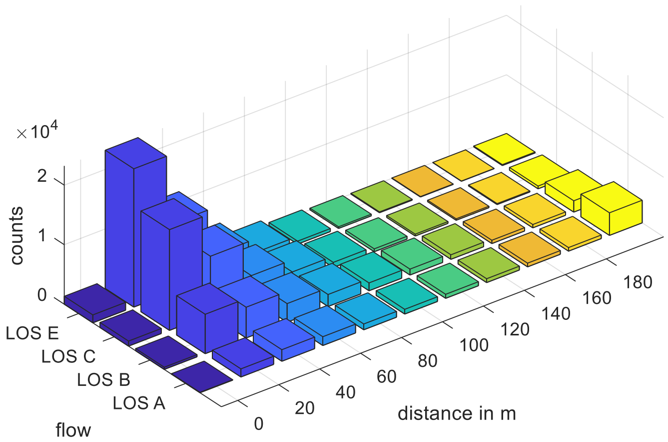


Figure 105. Bottleneck Onramp -Inter vehicle gap on rightmost lane - Measure simulation II (Speed+ Lane Change Advice)

Figure 105 presents the inter vehicle gap variation on the rightmost lane for the persistent lane change advice.

Figures 106-109 show cross-comparisons between baseline and measure simulations of the intervehicle gap on the rightmost lane for the different traffic densities (LOS). These plots represent the same cumulative variations shown in Figure 104 and Figure 105 with a different perspective so that more intuition can be drawn. Specifically, in the following 4 plots inter vehicle gaps for individual LOS values are presented for the baseline and two measure scenarios.

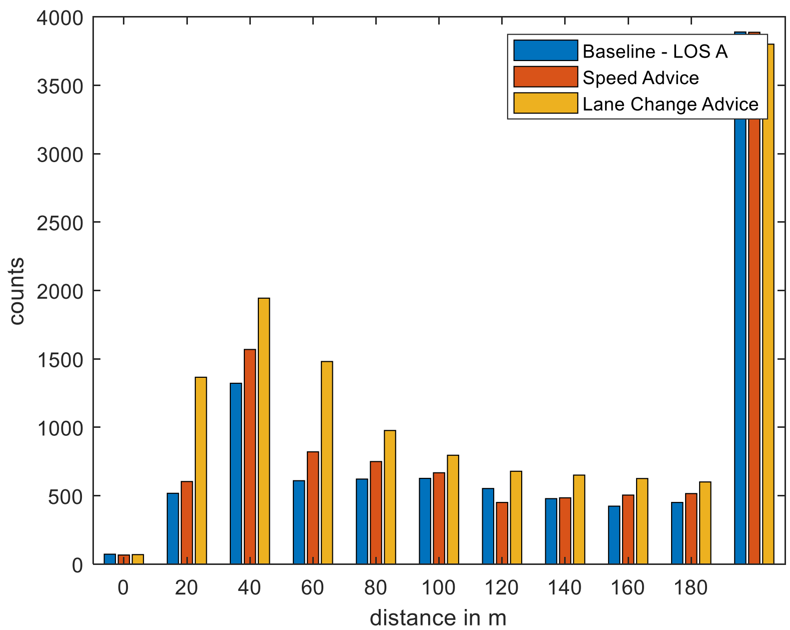


Figure 106. Bottleneck Onramp –Cross comparison of measures of intervehicle gap on rightmost lane- LOS A

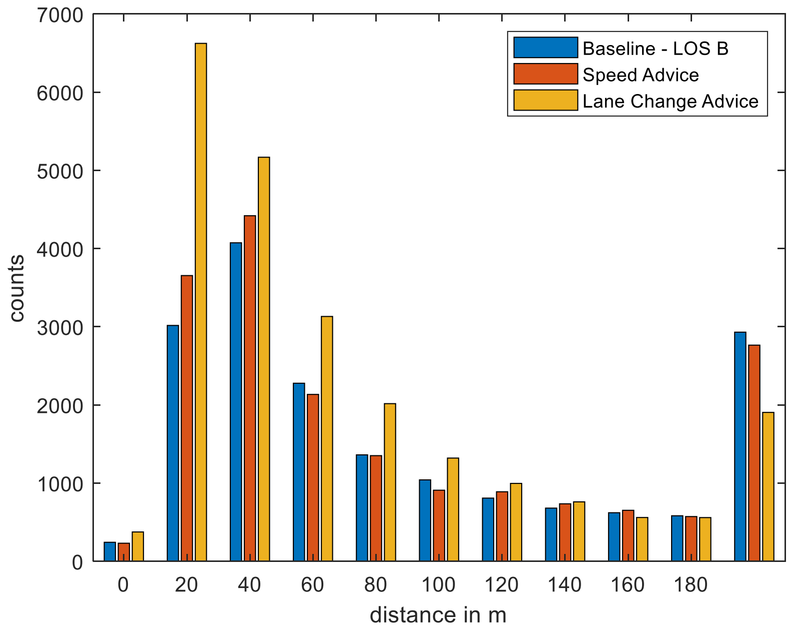


Figure 107. Bottleneck Onramp -Cross comparison of measures of intervehicle gap on rightmost lane- LOS B

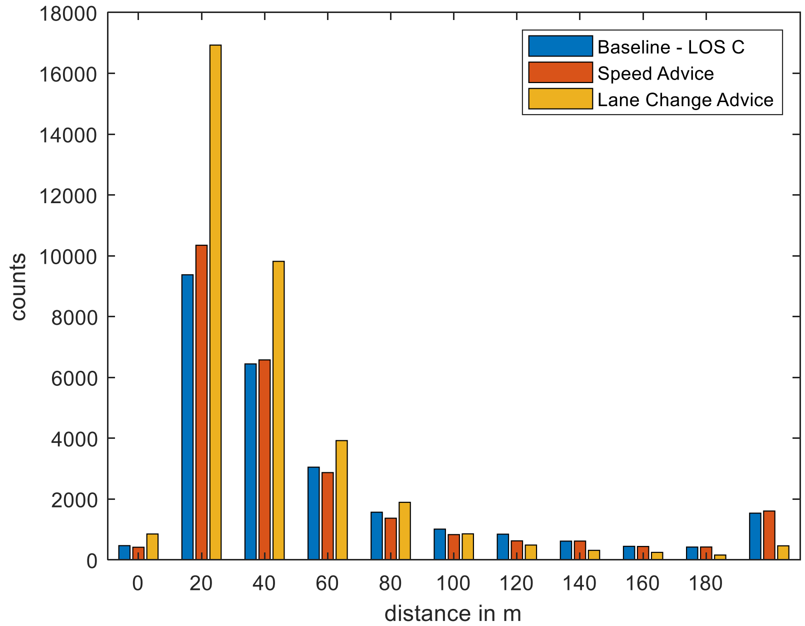


Figure 108. Bottleneck Onramp -Cross comparison of measures of intervehicle gap on rightmost lane- LOS C

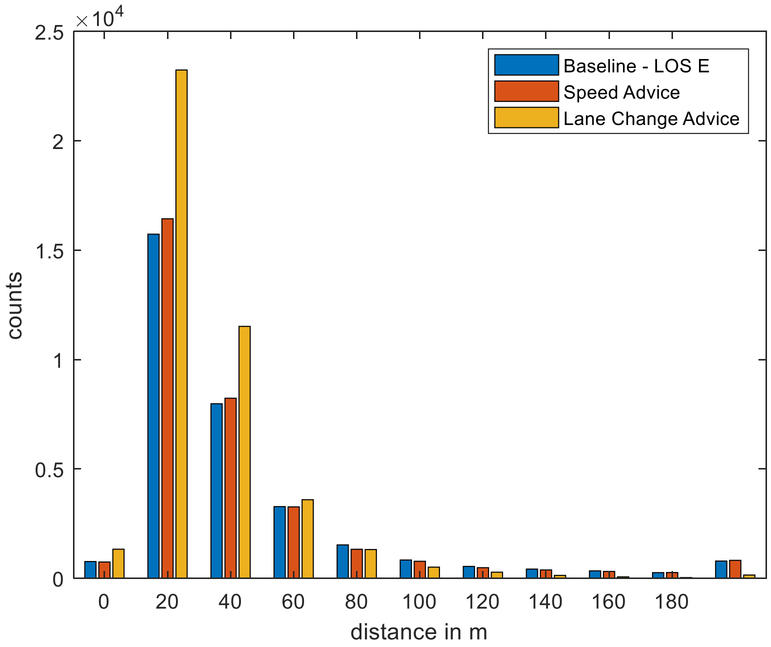


Figure 109. Bottleneck Onramp -Cross comparison of measures of intervehicle gap on rightmost lane- LOS E

Time Gap

The minium time gap (TGAP) between two vehicles is a measure of vehicle safety. As with all the performace indicators in submicroscopic simulation, the minimum time gap was evaluated only in segment 3 and for the time frame when the VuT is in the vicinity. If the time gap falls below the threshold of 10 seconds, then TGAP event is recorded. From each of this events the minimum gap is evaluated. The minima of these events are taken over a simulation and the result is input to to the histogramm of cumulated 60 simulation runs.

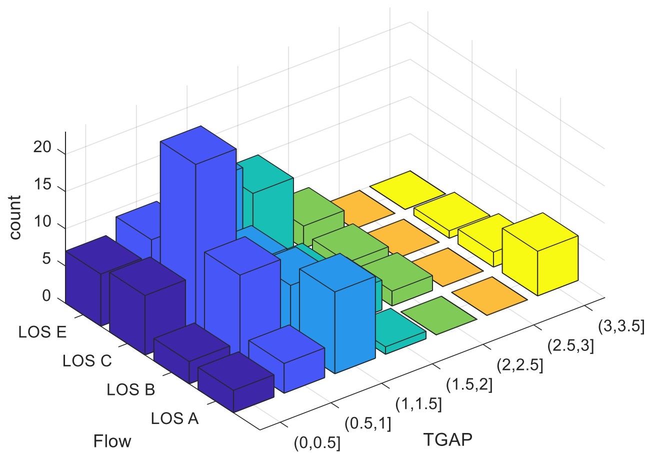


Figure 110. Bottleneck Onramp – Time Gap – Baseline

In Figure 110, TGAP variation for varying traffic densities and 0.5 s time-windows are shown for the baseline simulations.

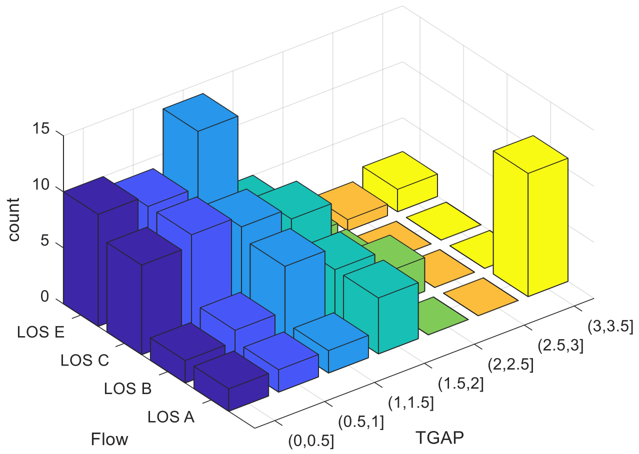


Figure 111. Bottleneck Onramp – Time Gap – Measure Speed Advice

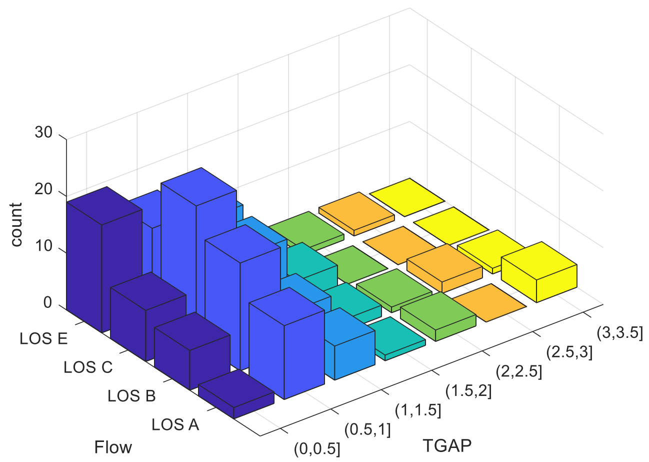


Figure 112. Bottleneck Onramp – Time Gap- Measure Speed+Lane Change Advice

Consecutively, Figure 111 and Figure 112 represent the TGAP distributions for the two measure scenarios. Based on these figures there is a clear trend for reduced TGAP values for increasing traffic densities in every case. Moreover, there is a clear shift to lower TGAP thresholds towards left, indicating reduced safety. Beyond this, no clear conclusions can be made due to the statistically low number of samples obtained during the experiments for KPI.

Time to Collision (TTC)

This KPI or metric is the most relevant metric for analysing safety as it is measure of the imminence of possible collisions and therefore assessment of critical traffic situations in microscopic and sub-microscopic traffic simulations. In analysing traffic conflicts and safety, TTC is proven to be an effective measure for rating the severity of traffic conflicts and for discriminating critical from normal behaviour. In chapter 0.1 the TTC as safety KPI is discussed in more detail.

The following figures, particularly Figure 113, Figure 114, Figure 115 and Figure 116 show the cumulative frequency of TTCs for varying traffic densities (i.e. for LOS A, LOS B, LOS C, and LOS E). In these plots the TTC variation was plotted for baseline and two measure scenarios.

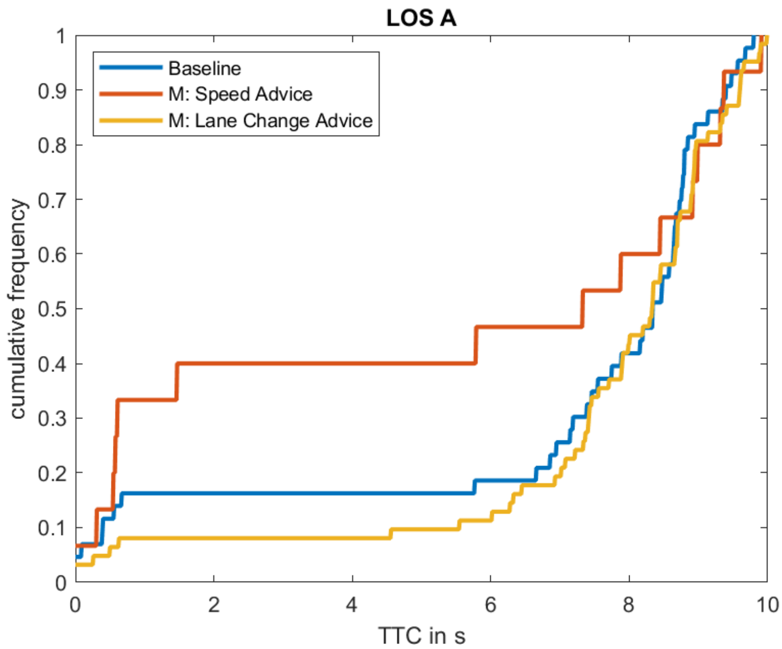


Figure 113. Bottleneck Onramp – cumulative TTC – LOS A

In Figure 113, the evaluation of TTC for LOS-A is illustrated. It is observed that the cumulative frequency of the TTC values of the measure simulation with “speed advice” message is higher than the cumulative frequency of the baseline TTCs. This means that there is a higher risk of an accident. On the other hand, the cumulative frequency of the TTCs of the measure simulations with “lane change advice” is lower. This can consequently be interpreted as a lower safety risk.

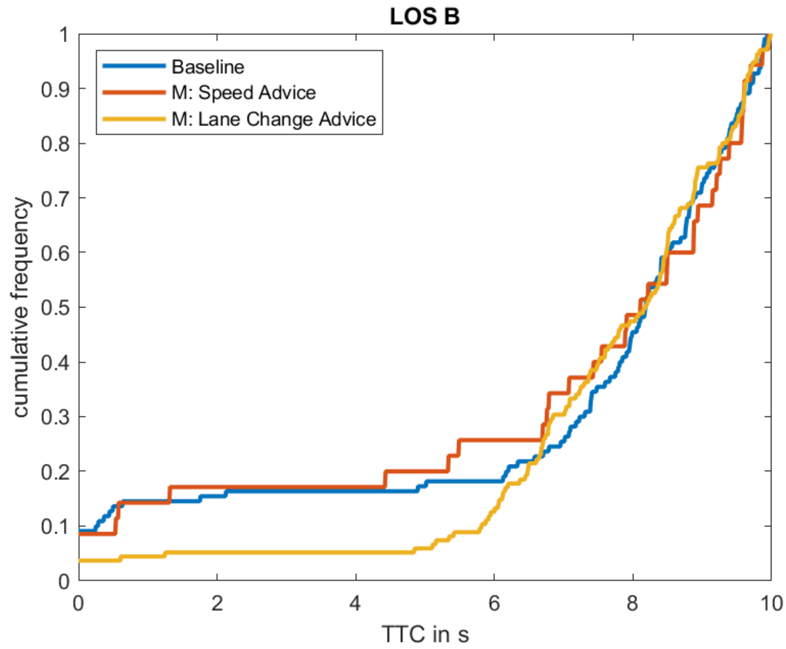


Figure 114. Bottleneck Onramp – cumulative TTC – LOS B

In Figure 114, the TTC for LOS-B is shown. We observe that the cumulative frequency of TTCs of the “speed advice” message is not significantly far away from that of the baseline simulation. Due to the smaller number of contributing events, it is difficult to make a statement whether it is an improvement or not. In the case of the “lane change advice” message the cumulative frequency of the measure simulation is lower, which is an indicator for an improvement for this traffic density.

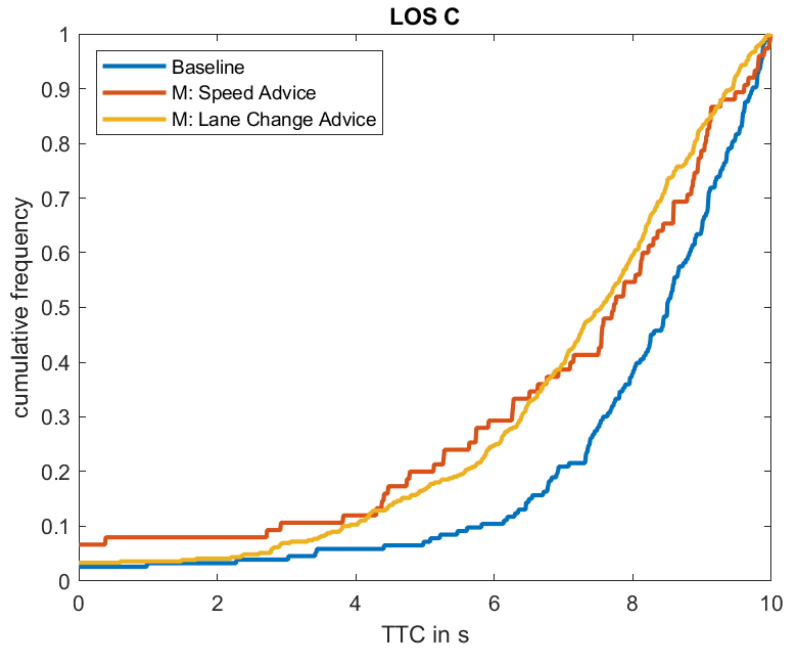


Figure 115. Bottleneck Onramp – cumulative TTC – LOS C

In Figure 115, corresponding to the TTC evaluation for LOS-C, it can be observed that the cumulative frequency of the TTCs in the case of the baseline is lower than the cumulative frequency of the TTCs of the two measure scenarios. Particularly, the TTC for "speed advice" message is clearly higher. This would indicate that the measure scenarios lead to a decrease in the level of safety.

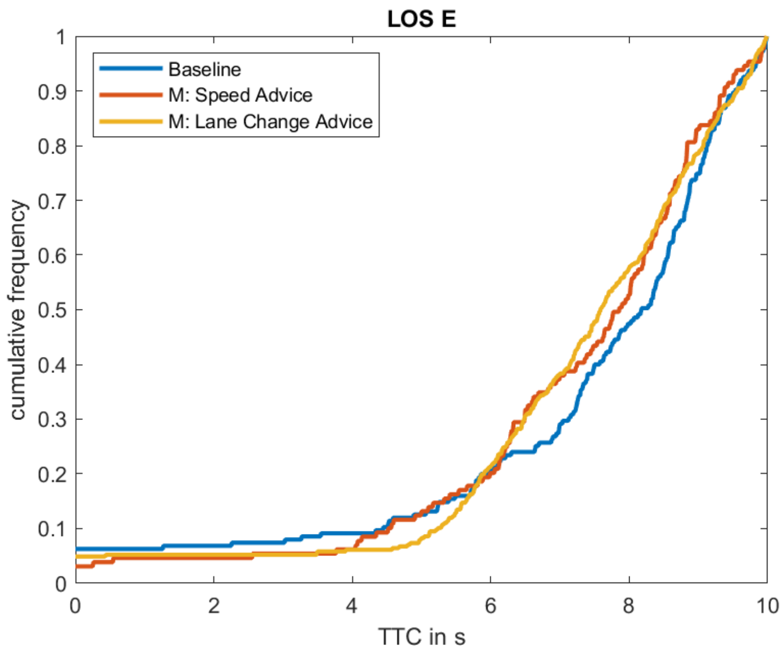


Figure 116. Bottleneck Onramp – cumulative TTC – LOS E

In the case of LOS-E traffic density, where the results are given in Figure 116, the curve of the cumulative frequency of TTCs of the baseline simulation is higher than that of the measure simulations. This is an indicator for an improvement due to the measure signals including "speed advice" and "lane change advice". This indicates that infrastructure messages can improve safety, as measured by the TTC at high traffic densities.

7.7.2 Results and KPI analysis – Bottleneck – Main Road:

<u>Traffic flow:</u>

The traffic flow is measured with detectors upstream of the onramp before the traffic from the main road merges into the main traffic. The vehicles from second 180 to 240 are counted and extrapolated to vehicles per hour. Afterwards, the measured traffic is averaged over 60 experiments. The following tables show the results.

Table 32. Bottleneck Main Road - Traffic Flow Estimated - Baseline

SC3UC3, Bottleneck, Main road, Baseline				
Flow [veh/h]	LOS A	LOS B	LOS C	LOS E
Mean	1593	2995	3995	4567
Std	356.5	611.9	532.5	604.2
Min	660	1560	2760	3360
Max	2340	4440	5280	5820

Table 33. Bottleneck Main Road - Traffic Flow Estimated – Measure Speed Advice

SC3UC3, Bottleneck, Main road, Speed advice				
Flow [veh/h]	LOS A	LOS B	LOS C	LOS E
Mean	1584	2977	4000	4573
Std	355.2	596.1	554.2	574.5
Min	660	1560	2760	3360
Max	2460	4320	5280	5580

Table 34. Bottleneck Main Road - Traffic Flow Estimated – Measure Speed+Lane Change Advice

SC3UC3, Bottleneck, Main road, Lane change advice				
Flow [veh/h]	LOS A	LOS B	LOS C	LOS E
Mean	1576	2971	3819	4026
Std	350.2	616.8	521.5	457
Min	660	1140	2160	2700
Max	2460	3900	4860	5160

Mean Speed

The mean speed is calculated as in the scenario before, only in segment 3 of every vehicle class. Beside the mean speed value, the following tables (Tables 36-38) include the standard deviation as well as the maximum speed. For a detailed description it is referred to the mean speed description of the previous scenario.

Table 35. Bottleneck Main Road - Mean Speed - Baseline

Traffic Density	Vehicle Type	Mean Speed km/h	Deviation km/h	Maximum Speed km/h
LOS A	Conventional	109.92	3.39	130
	Automated	92.48	3.85	130
	Motorcycle	98.44	8.86	126.5
	Truck	85.67	1.57	87.84
	Trailer	80.09	1.37	80.64

LOS B	Conventional	102.88	3.5	130
	Automated	87.92	3.08	130
	Motorcycle	94.22	7.71	127.98
	Truck	83.88	3.09	87.84
	Trailer	76.34	4.39	80.64
LOS C	Conventional	96.87	5.04	130
	Automated	83.42	5.52	130
	Motorcycle	91.11	6.69	129.89
	Truck	78.03	6.65	87.84
	Trailer	73.9	5.07	80.64
LOS E	Conventional	91.73	5.36	130
	Automated	81.27	5.48	130
	Motorcycle	91.37	7.64	130
	Truck	71.68	7.72	87.84
	Trailer	66.92	6.56	80.64

Table 36. Bottleneck Main Road - Mean Speed - Measure Speed Advice

Traffic Density	Vehicle Type	Mean Speed km/h	Deviation km/h	Maximum Speed km/h
LOS A	Conventional	98.89	1.59	130
	Automated	90.87	3.48	128.74
	Motorcycle	94.32	6.15	114.66
	Truck	85.41	1.71	87.84
	Trailer	79.96	1.72	80.64
LOS B	Conventional	96.3	2.08	130
	Automated	86.49	3.04	122.98
	Motorcycle	90.63	6.83	113.04
	Truck	83.29	3.47	87.84
	Trailer	75.54	4.72	80.64
LOS C	Conventional	92.23	3.86	130
	Automated	82.42	4.72	130
	Motorcycle	89.69	5.57	116.14
	Truck	77.84	5.98	87.84
	Trailer	73.5	4.8	80.64
LOS E	Conventional	88.74	4.31	130
	Automated	80.86	4.93	127.62
	Motorcycle	88.47	6.91	111.6
	Truck	71.8	7.47	87.84
	Trailer	67.42	6.2	80.64

Table 37. Bottleneck Main Road - Mean Speed - Measure Speed+Lane Change Advice

Traffic Density	Vehicle Type	Mean speed km/h	Deviation km/h	Maximum Speed km/h
LOS A	Conventional	96.114	4.122	130
	Automated	89.629	4.5374	128.92
	Motorcycle	93.006	6.7152	114.66
	Truck	85.277	2.0909	87.84
	Trailer	79.817	2.6931	80.64
LOS B	Conventional	90.707	5.5516	130
	Automated	84.241	4.8595	122.98
	Motorcycle	86.338	6.6524	113.4
	Truck	82.505	4.1398	87.84
	Trailer	77.319	3.8248	80.64
LOS C	Conventional	84.045	6.3363	130
	Automated	80.19	5.7117	130
	Motorcycle	82.867	7.1944	116.06
	Truck	77.472	5.6834	87.84
	Trailer	74.557	4.4449	80.64
LOS E	Conventional	75.725	6.9634	130
	Automated	73.766	6.06	127.73
	Motorcycle	78.671	7.0143	111.56
	Truck	68.905	8.1724	87.84
	Trailer	66.56	6.5289	80.64

Figure 117 illustrates the mean speed of conventional vehicles in segment 3 for the baseline as well as for both measure simulations. The mean speed value decreases with increasing traffic. The figure shows also that the mean speed is reduced in the measure simulations due to the speed advice, which is also active in the second measure simulation (yellow line). In case of the lane change advice, automated vehicles move away from the first lane and cause a higher traffic volume on the second and third lane which entails a decreasing mean speed furthermore.

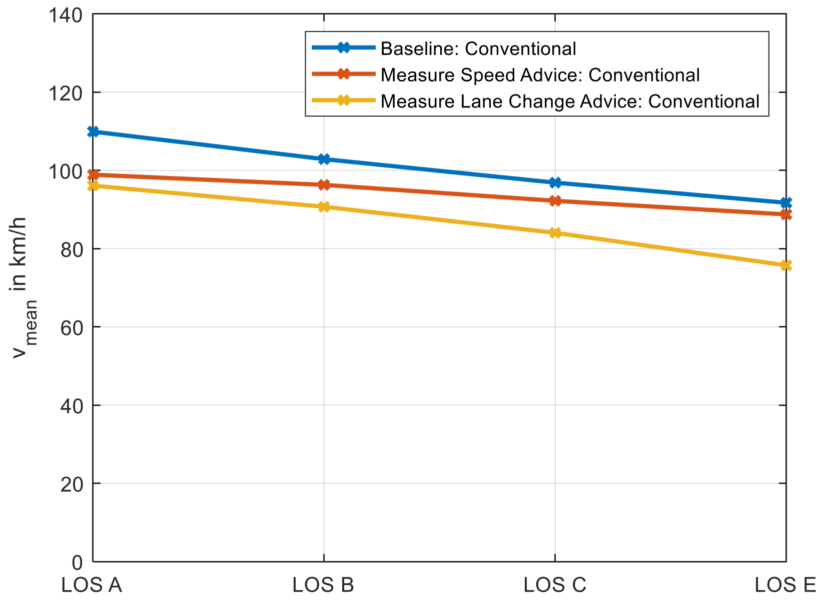


Figure 117. Bottleneck Main Road - Mean Speed – Conventional Vehicles

In Figure 118, the mean speed value for automated vehicles in segment 3 for all three simulations is presented. A comparison between Figures 117 and 118 shows that automated vehicles exhibit a lower mean speed than conventional vehicles. As the mean speed is very low, Figure 118 shows that the speed advice has no significant effect on the mean speed.

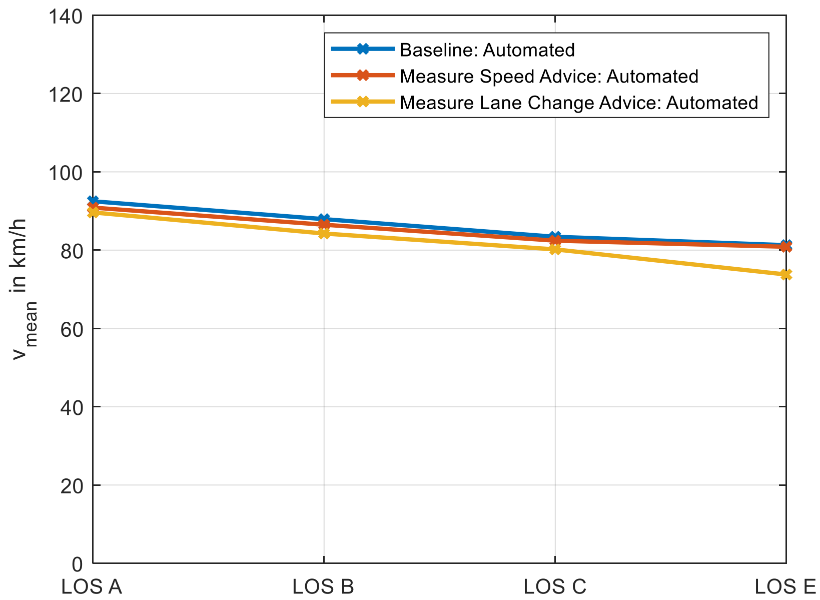


Figure 118. Bottleneck Main Road -Mean Speed – Automated Vehicles

In Figure 119 the mean speed value for trucks and trailers in all three simulations can be seen. Again, the mean speed decreases with increasing traffic flow. Only very small changes due to the measures can be observed. The reason why no effects can be seen is, that the mean speed in general is smaller than the new speed limit in the measures.

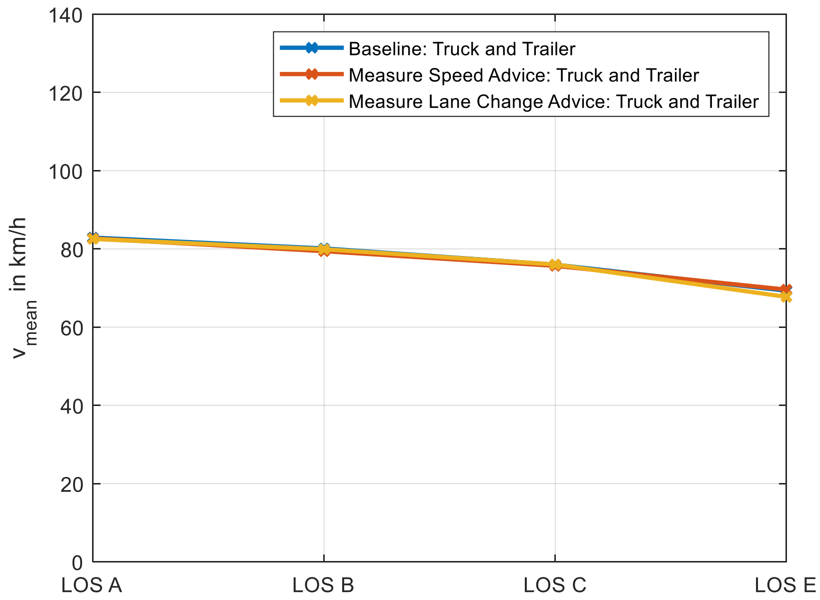


Figure 119. Bottleneck Main Road -Mean Speed - Truck and Trailer

Number of Stops

The following Table includes the number of stops of all vehicles in segment 3 due to vehicles coming from the onramp.

Table 38. Bottleneck - Main Road - Number of Stops

		Baseline Number of Stops		Measure I Number of Stops		Measure II Number of Stops	
		Mean	Deviation	Mean	Deviation	Mean	Deviation
LOS A	Conventional	0	0	0	0	0	0
	Automated	0	0	0	0	0	0
	Motorcycle	0	0	0	0	0	0
	Truck	0	0	0	0	0	0
	Trailer	0	0	0	0	0	0
	CarICOS	0	0	0	0	0	0
LOS B	Conventional	0	0	0	0	0	0
	Automated	0	0	0	0	0	0
	Motorcycle	0	0	0	0	0	0
	Truck	0	0	0	0	0	0
	Trailer	0	0	0	0	0	0

	CarICOS	0	0	0	0	0	0
LOS C	Conventional	0.02	0.14	0.01	0.1	0.02	0.14
	Automated	0	0	0	0	0	0
	Motorcycle	0	0	0	0	0	0
	Truck	0	0	0	0	0	0
	Trailer	0	0	0	0	0	0
	CarICOS	0	0	0	0	0	0
LOS E	Conventional	0.02	0.15	0.02	0.12	0.04	0.2
	Automated	0	0	0	0	0	0
	Motorcycle	0	0	0	0	0	0
	Truck	0.25	0.46	0.25	0.46	0.25	0.46
	Trailer	0	0	0	0	0	0
	CarICOS	0	0	0	0	0	0

Travel time

Table 40 lists the mean travel time and its deviation for all simulations, level of services and vehicle types. The mean traveltime was calculated of all vehicle classes as long as they drive in segment 3.

Table 39. Bottleneck Main Road – Travel time

		Baseline		Measure Speed Advice		Measure Lane Change Advice	
		Mean s	Deviation s	Mean s	Deviation s	Mean s	Deviation s
LOS A	Conventional	31.39	0.88	35.18	0.41	36.24	1.51
	Automated	37.2	1.53	37.86	1.37	38.19	1.93
	Motorcycle	36.04	5.12	38.24	3.99	38.06	3.43
	Truck	40.61	0.87	40.74	0.91	40.69	0.9
	Trailer	43.15	0.31	43.21	0.47	43.23	0.55
LOS B	Conventional	33.11	1.15	35.57	0.63	37.76	2.06
	Automated	38.63	1.58	39.4	1.67	40.16	2.3
	Motorcycle	38.11	4.7	39.98	4.51	41.47	4.43
	Truck	41.27	1.89	41.49	2.05	41.52	1.79
	Trailer	44.59	2.87	44.94	2.98	44.02	1.5
LOS C	Conventional	34.28	1.27	36.35	1.07	38.9	2.15
	Automated	39.82	2.32	40.43	2.15	40.61	2.19
	Motorcycle	38.37	3.84	38.61	2.87	40.86	3.82
	Truck	42.16	2.86	42.37	2.78	42.63	2.79
	Trailer	46.68	4.17	46.65	3.79	45.37	2.86
LOS E	Conventional	35.21	1.9	36.85	1.31	40.69	2.98
	Automated	40.26	2.49	40.41	2.11	42.47	2.84
	Motorcycle	38.01	3.27	38.85	2.98	42.47	4.61
	Truck	44.83	4.57	44.68	4.19	46.13	5.2
	Trailer	48.33	4.45	48.21	4.45	47.97	4.81

The following 3 figures show the travel time in segment 3 for different vehicle types. The travel time is plotted against the traffic flow for the baseline (blue line), for measures I (red line) and for measure II (yellow line). As expected, Figures 120-122 show increasing travel times with higher traffic flows.

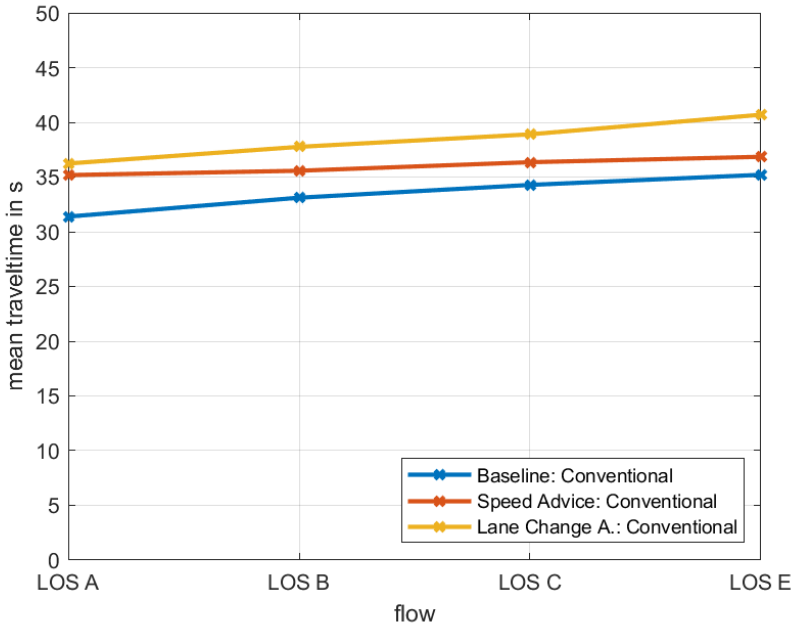


Figure 120. Bottleneck Main Road -Travel Time in Segment 3, Conventional Vehicles

Figure 120 presents the travel time of conventional vehicles in segment 3. It can be seen that the travel time of the conventional vehicles increase in both measures in comparison with the baseline. This is mainly due to the reduction of the allowed speed from 130 km/h to 100 km/h in both cases. In the case of the lane change advice the velocity, it is suspected, that the velocity decreases due to the higher density of vehicles on the middle lane as well as on the leftmost lane. The speed on rightmost lane is determined due to slower trucks and trailers. Overall, the speed is in case of the lane change advice lower and therefore the travel time is higher.

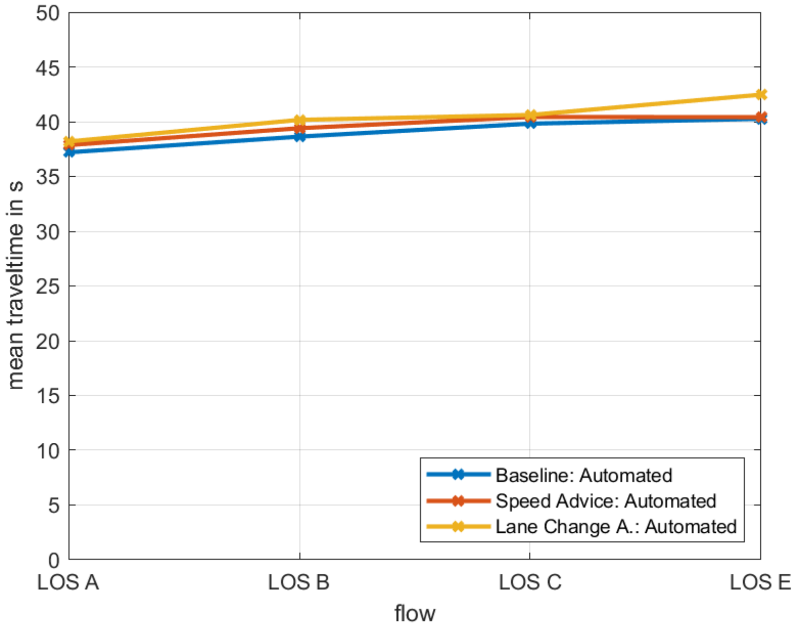


Figure 121. I Bottleneck Main Road - Travel Time in Segment 3, Automated Vehicles

In Figure 121 the travel time of automated vehicles is shown. In comparison to conventional vehicles there is nearly no increase of the travel time. Here, the mean speed is very small in general and that is the reason why speed advices have no effect on travel times.

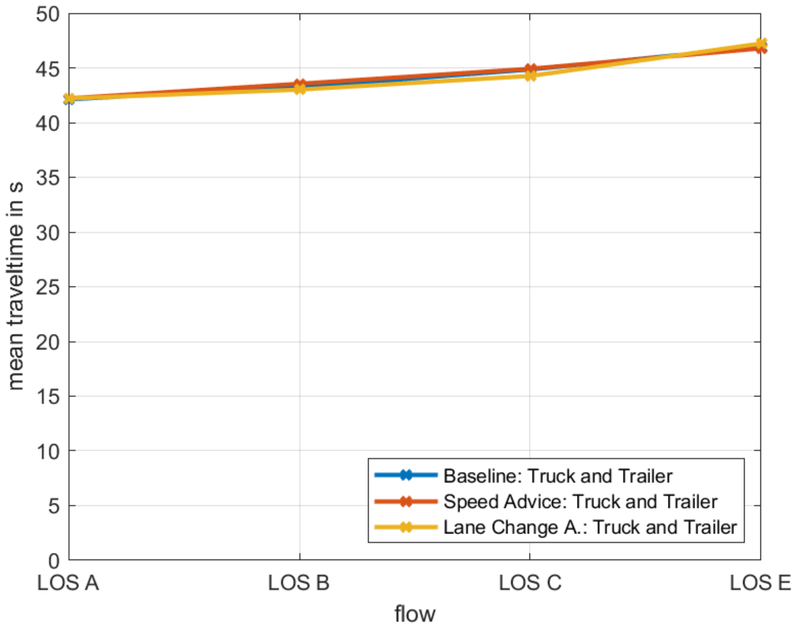


Figure 122. Bottleneck Main Road - Travel time in Segment 3, Truck and Trailer

In Figure 122 the average travel time of truck and trailers is depicted. Since the mean speed trucks and trailers is below the speed advice, there is also nearly no effect of the measures on the travel time of trucks and trailers.

Intervehicle Gap on Rightmost Lane:

The gaps between vehicles on the rightmost lane of the main road is an indirect indicator of how easy a vehicle coming from the onramp can merge into the main traffic. In other words, this measure (KPI) quantifies the difficulty for vehicles coming from an onramp to merge into the traffic on the main road.

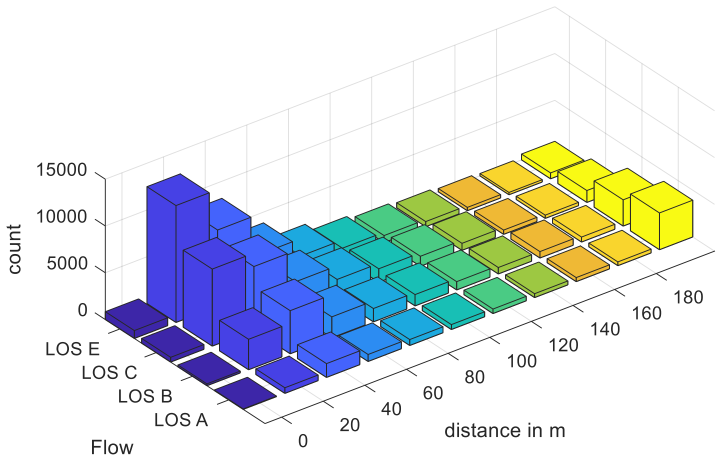


Figure 123. Bottleneck Main Road – Inter vehicle gap on rightmost lane - Baseline

Figure 123 depicts the situation for the baseline simulation. For small traffic densities, particularly for LOS A there are very few intervehicle gaps below 200 m. With increasing traffic flow densities, the number of smaller inter vehicle gaps, especially around 20m and 40m values, statistically increase with increasing flow density as observed from Figure 123.

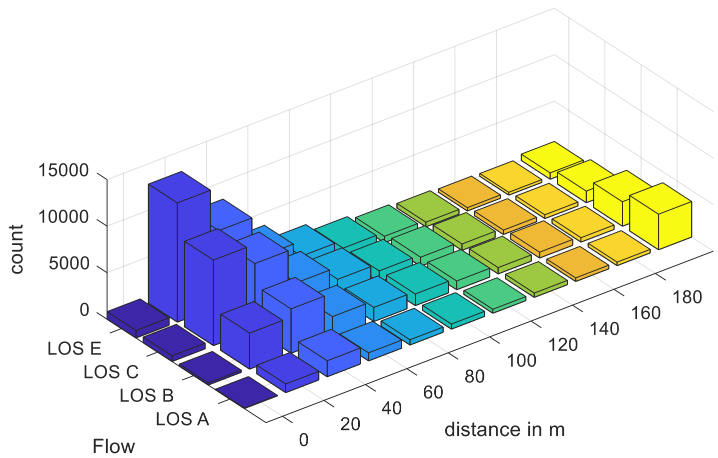


Figure 124. Bottleneck Main Road – Inter vehicle gap on rightmost lane – Measure Speed Advice

In Figure 124 the situation for the measure scenario with persistent speed advice is shown. The result shows nearly the same characteristics as the baseline scenario.

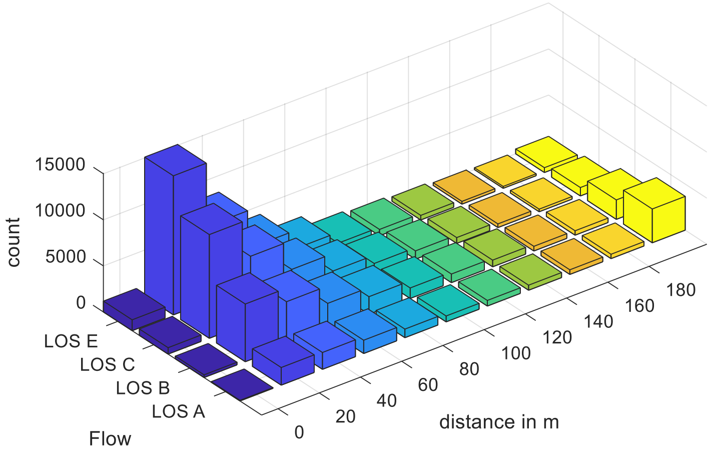


Figure 125. Bottleneck Main Road – Inter vehicle gap on rightmost lane – Measure Speed+Lane Change Advice

In Figure 125 the similar result for the measure scenario with the persistent lane change advice is shown. As with the previous two cases, the characteristics and trends are similar to the baseline and the speed advice measure scenarios. It interesting to observe however that the total number of inter vehicle gaps in the 20 m range has increased, particularly for higher traffic densities. This can be seen more clearly in the following cross-comparison plots of measure and base line scenarios for specific LOS values in Figures 126 -129.

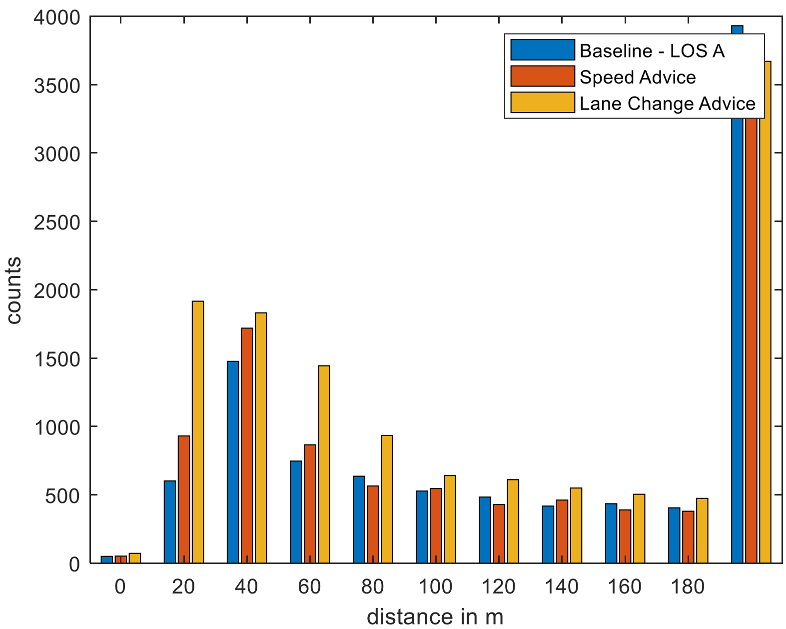


Figure 126. Bottleneck Main Road –Cross comparison of measures of intervehicle gap on rightmost lane- LOS A

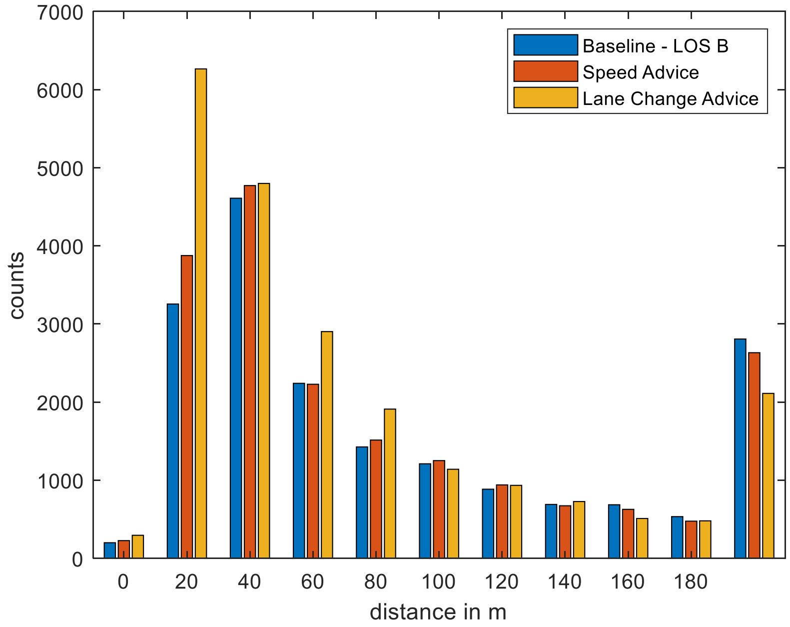


Figure 127. Bottleneck Main Road –Cross comparison of measures of intervehicle gap on rightmost lane- LOS B

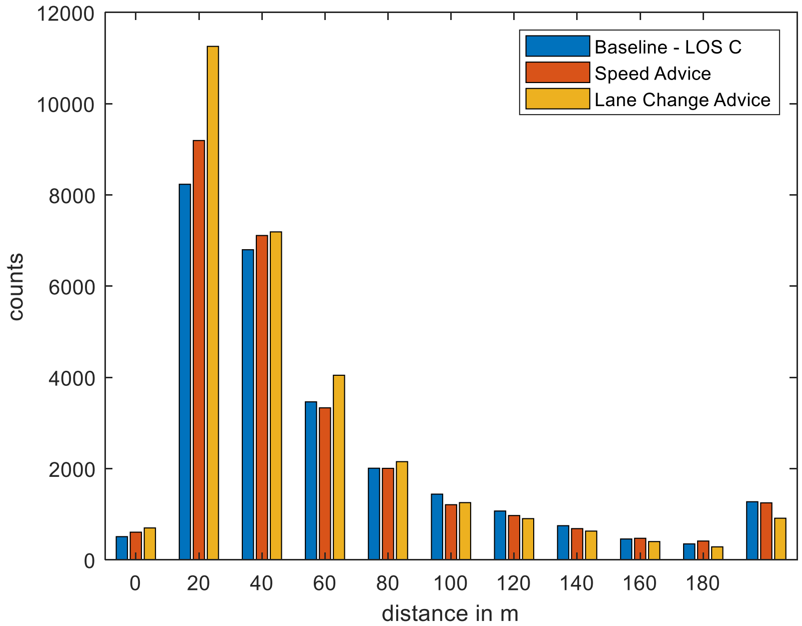


Figure 128. Bottleneck Main Road –Cross comparison of measures of intervehicle gap on rightmost lane- LOS C

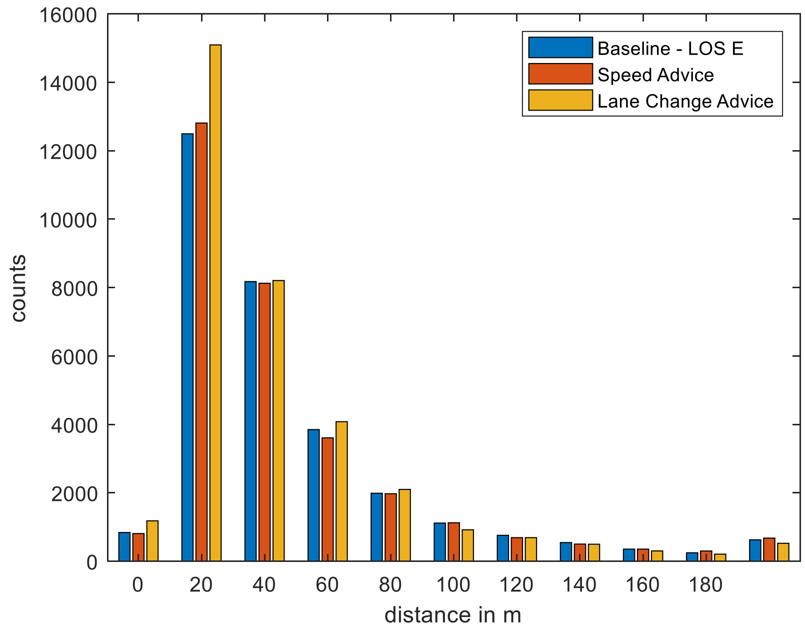


Figure 129. Bottleneck Main Road –Cross comparison of measures of intervehicle gap on rightmost lane- LOS E

In all traffic densities (i.e., LOS levels) there are higher occurrences of smaller inter vehicle gap values in the case of the measure scenarios with lane change advice than in the baseline scenario. This result may be caused by the fact that automated vehicles are encouraged to leave the rightmost lane, but no rule prevents other (manual driven) vehicles to fill up the gap. Also, since there is a combined mean speed advice message in the case of the measure scenario with the lane change advice, the lower inter vehicle gap values are believed to be more.

Time Gap

Again, we look at the minium time gap (TGAP) between two vehicles as a measure of vehicle safety. As with all the other performace indicators in submicroscopic simulation, the minimum time gap was evaluated only in segment 3 and for the time frame when the VuT is in the vicinity. If the time gap falls below the threshold of 10 seconds, then TGAP event is recorded and accumulated. From each of this events the minimum gap is evaluated.

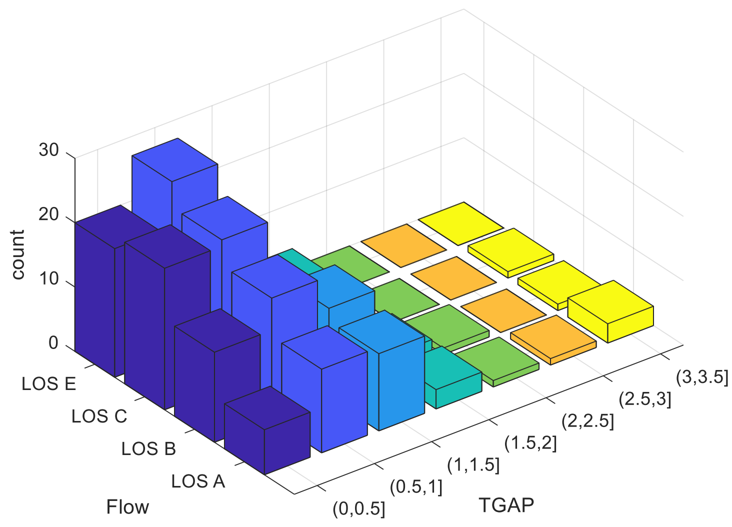


Figure 130. Bottleneck Main Road – Time Gap - Baseline

Figure 130 shows the time gap distribution for the baseline simulation. Here we have increasing time gap counts with increasing LOS or traffic densities. Also, we observe that most critical time gaps are concentrated in the 0-2 seconds window.

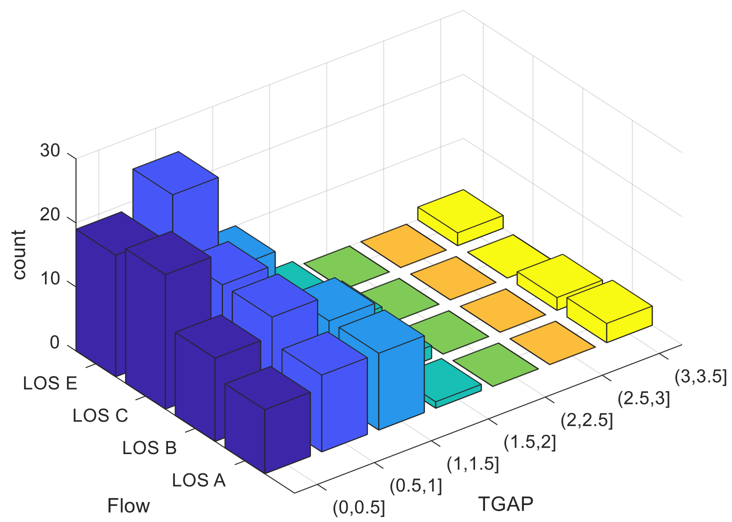


Figure 131. Bottleneck Main Road – Time Gap – Measure Speed Advice

In Figure 131 the cumulative time gaps occurrences for the measure scenario with persistent speed advice are plotted. Here we observe that the overall trends are not very far away from the baseline scenario except for a small reduction in the time gap values for medium LOS levels in the 0,5-1 seconds interval.

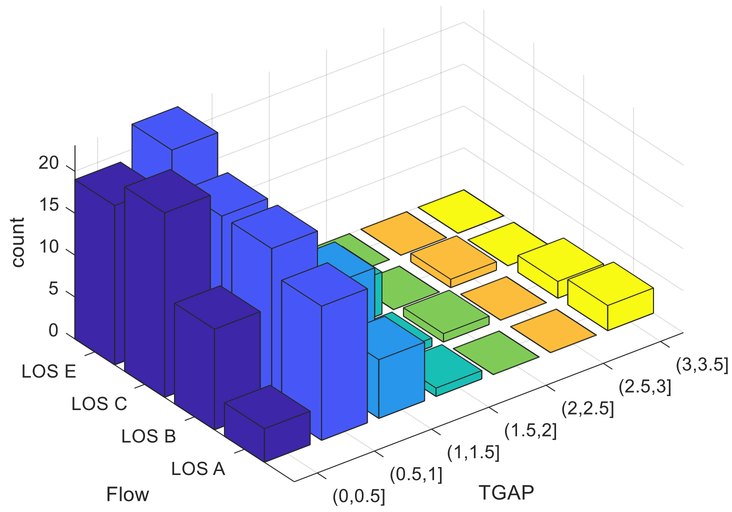


Figure 132. Bottleneck Main Road – Time Gap – Measure Speed+Lane Change Advice

In Figure 132 the cumulative time gap for the measure scenario with lane change advice are shown. Here as well the trends are similar to that of the baseline scenario, with the only exception of the significantly increased counts for the time gap values in the 0,5-1 seconds interval.

<u>Time to Collision (TTC)</u>

TTC as safety KPI is discussed in chapter 7.1.3 For this specific use case, The following figures, particularly Figures 133-136 the cumulative frequency of TTCs for varying traffic densities (i.e. for LOS A, LOS B, LOS C, and LOS E). In these plots the TTC variation was plotted for baseline and two measure scenarios.

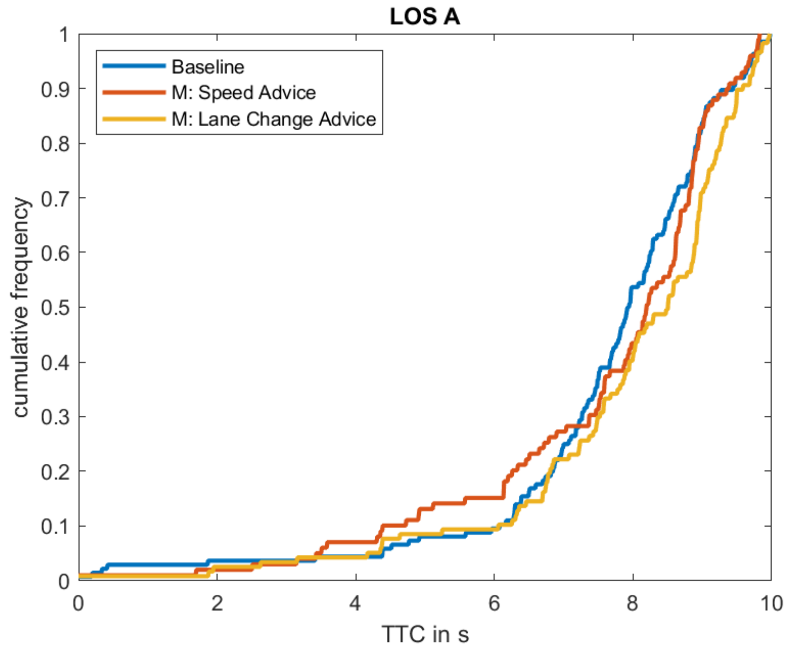


Figure 133. Bottleneck Main road – cumulative TTC – LOS A

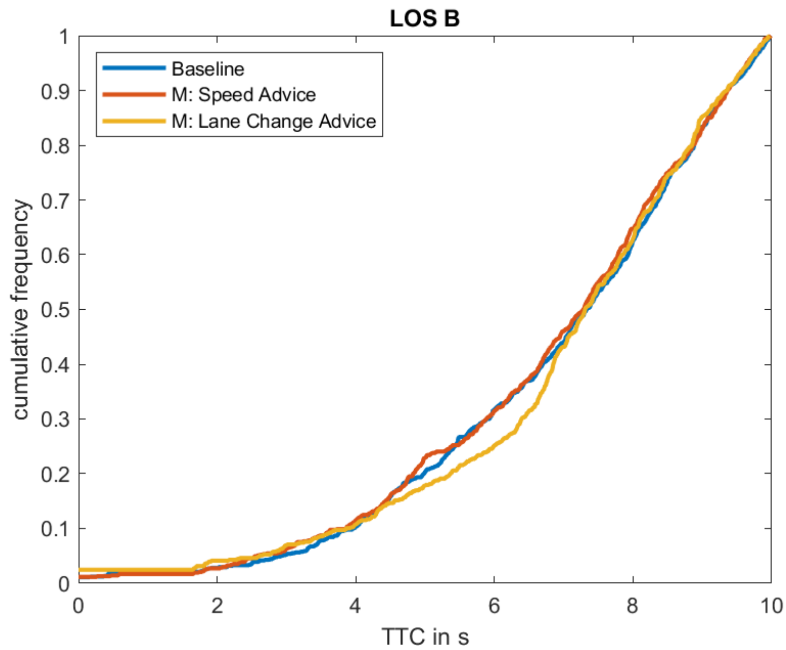


Figure 134. Bottleneck Main road – cumulative TTC – LOS B

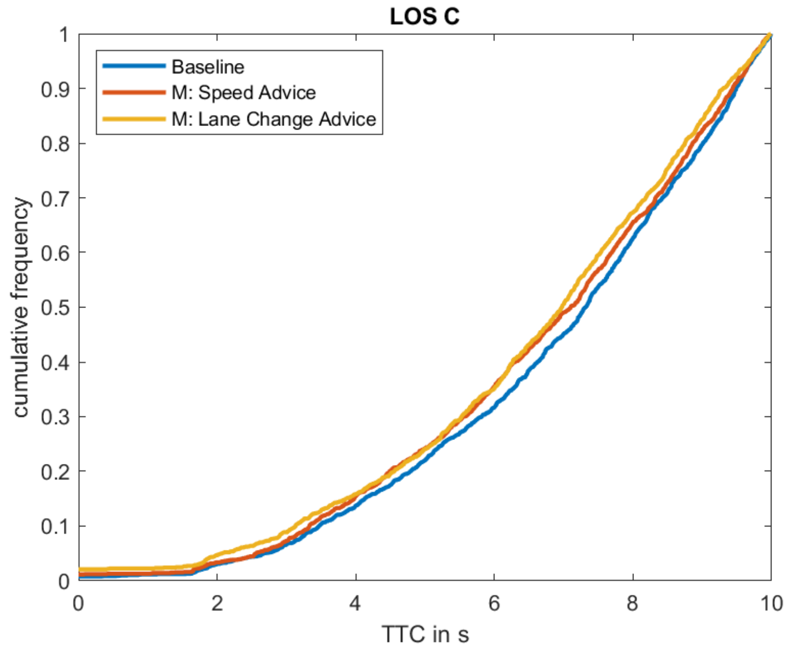


Figure 135. Bottleneck Main road – cumulative TTC – LOS C

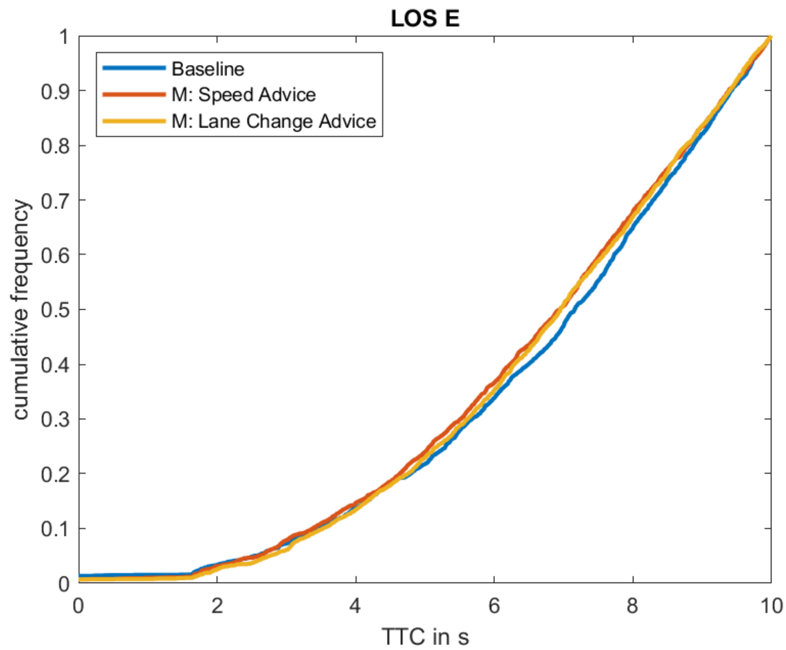


Figure 136. Bottleneck Main road – cumulative TTC – LOS E

As observable from the last 4 figures, the variation of TTC for this specific use case is very similar for the baseline and 2 measure scenarios. Therefore, no concrete statements could be made for the influence of the measure messages for this specific use case. The reason is related to the small number of statistical occurrences. From the obtained results, it can be conjectured that the number of experiments has a big influence on the results, which is strictly restricted in sub-microscopic simulation due to size of the map data and the number of traffic objects available in simulation. Especially, the TTC as a KPI sub-microscopic simulations perspective represents a challenge. The reason is the behaviour of the car following and the lane change models in SUMO, and since these always tend to keep a safe distance to a lead vehicle. This fact itself, makes it statistically very difficult to get a reasonable number of TTC values below a specific threshold when the number of experiments is low.

7.7.3 Results and KPI analysis – Roadworks zone:

This analysis consists of two different parts. First microscopic traffic parameters will be analysed, i.e., mean speed and traveltime. In this part only very small differences between baseline and measure can be expected, because only the VuT is directly influcenced by the measure. In the second part the behavior of the VuT itself will be analysed. This part contains for instance number of stops and number of merges of the VuT.

Traffic flow

The traffic flow was measured with a detector 310 m after the beginning of segment 3. The starting point of segment 3 is also the starting position of the roadworks zone with only 2 drivable lanes. The traffic flow is measured between simulation seconds 120 and 180. During this time period, the VuT in the submicroscopic simulation passes through the detectors, if it has not stopped before the roadworks zone.

Table 40. Roadworks zone, Traffic flow measured

	Traffic flow, Baseline				Traffic flow, Measure			
	Mean veh/h	Deviation veh/h	Min veh/h	Max veh/h	Mean veh/h	Deviation veh/h	Min veh/h	Max veh/h
LOS_A	1637	418	420	2580	1643	428.1	420	2580
LOS_B	2910	473.2	1402	4380	2963	475.3	1402	3780
LOS_C	3350	511.5	2340	4440	3370	515.5	2160	4260
LOS_E	3485	478.3	1620	4260	3483	462	1620	4200

According to the Table 41 summarising the results, it is observable that the mean traffic flow rates in all the traffic density seem to be nearly the same. However the extreme values seem to be slightly affected. Also when we look from the demanded traffic flow rates perspective, in LOS A and LOS B the demanded and measured traffic flow rates are in agreement, whereas the measured traffic flow LOS C about a quater lower than the demanded traffic flow and in LOS E about a third lower. This is due to the reduced capacity of the road as a result of the blocked rightmost lane.

Mean Speed

This section summarizes the mean speed for two segments for the baseline simulation as well as the measure simulation. The corresponding segments are the Segment-2 as well as the segment-3. Since only the ego vehicle is affected by the measure, the mean speed parameter should be the same for the baseline as well as for the measure which can be seen in Figure 137 and Figure 138 . A comparison of the mean speed in both segments shows that the mean speed decreases in Segment-2 while it is nearly constant in Segment-3. The reason for the decreasing mean speed in Segment-2 is the lane reduction and an oncoming congestion. This entails also low traffic in Segment-3 and same levels of mean speed observed. A slowly declining trend in the mean speed was also observed for longer simulation times in the relevance zones.

Table 42 includes the mean speed of all vehicles in Segment-3 and **Error! Reference source not found.** summarizes the results for the mean speed in Segment-2. The mean speed is measured for each vehicle type separately during a time slot of 120 seconds. This time slot ranges from second 120 to 240 and matches the time frame when the VuT passes from the Segment-3 (of course when and if it has not stopped before the roadwork zone within Segment-2)

Table 41. Roadworks zone, Mean speed in Segment 3, Baseline

Traffic Density	Vehicle Type	Baseline			Measure		
		Mean Speed km/h	Deviation km/h	Max. Speed km/h	Mean Speed km/h	Deviation km/h	Max. Speed km/h
LOS A	Conventiona	97.42	2.92	100.01	97.66	2.81	100.01
	Automated	90.42	3.59	124.24	90.29	3.56	124.24
	Motorcycle	96.57	6.12	100.01	96.35	6.09	100.01
	Truck	85.37	2.12	87.84	85.18	2.19	87.84
	Trailer	80.24	1.42	80.64	80.4	1.1	80.64
LOS B	Conventiona	96.47	3.04	100.01	96.64	3.14	100.01
	Automated	87.22	3.4	128.74	87.48	3.43	128.74
	Motorcycle	90.3	6.78	100.01	89.54	6.21	100.01
	Truck	83.8	2.37	87.84	83.77	2.37	87.84
	Trailer	78.79	1.48	80.64	78.81	1.63	80.64
LOS C	Conventiona	94.41	3.87	130	94.18	3.9	130
	Automated	86.28	3.38	123.19	86.39	3.28	123.19
	Motorcycle	88.5	6.39	100.01	88.86	6.45	100.01
	Truck	81.86	2.8	87.84	82.14	2.6	87.84
	Trailer	77.36	2.22	80.64	77.32	2.55	80.64
LOS E	Conventiona	93.97	3.42	100.01	93.93	3.31	100.01
	Automated	86.83	2.82	111.46	86.75	3.01	111.46
	Motorcycle	90.19	5.83	100.01	89.56	5.59	100.01
	Truck	80.98	3.46	87.84	80.65	3.53	87.84
	Trailer	77.35	2.58	80.64	77.05	2.62	80.64

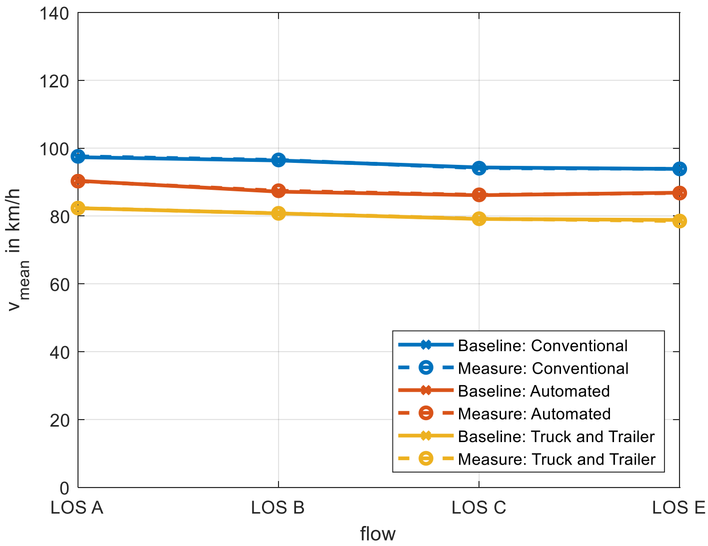


Figure 137. Roadworks zone, Mean Speed in Segment 3

Table 42. Roadworks zone, Mean speed in Segment 2

Traffic Density	Vehicle Type	Baseline Mean Speed km/h	Baseline Deviation km/h	Baseline Max. Speed km/h	Measure Mean Speed km/h	Measure Deviation km/h	Measure Max. Speed km/h
LOS A	Conventional	99.45	7.62	130	100	7.49	130
	Automated	89.15	5.5	130	89.2	5.45	130
	Motorcycle	95.23	13.09	125.14	95.34	13.05	126.29
	Truck	84.6	4.06	87.84	84.91	3.38	87.84
	Trailer	79.11	2.51	80.64	79.36	1.57	80.64
LOS B	Conventional	93.65	7.05	130	94.73	6.61	130
	Automated	81.18	6.24	130	82.19	5.55	128.74
	Motorcycle	84.37	9.18	122.9	84.55	7.26	122.9
	Truck	79.24	5.96	87.84	80.06	4.6	87.84
	Trailer	74.91	4.88	80.64	75.78	3.84	80.64
LOS C	Conventional	81.4	6.41	130	81.67	6.39	130
	Automated	72.39	5.8	129.42	72.87	5.71	129.42
	Motorcycle	74.98	9.55	126.36	75.42	8.84	126.07
	Truck	71.19	5.58	87.84	71.8	5.16	87.84
	Trailer	70.51	4.8	80.64	70.91	4.4	80.64
LOS E	Conventional	72.07	5.29	130	71.81	5.31	130
	Automated	65.25	4.77	116.68	65.44	4.6	116.68
	Motorcycle	69.07	7.49	130	68.33	7.05	130
	Truck	64.42	4.82	87.84	65.35	4.37	87.84
	Trailer	64.49	5.4	80.64	65.24	5.14	80.64

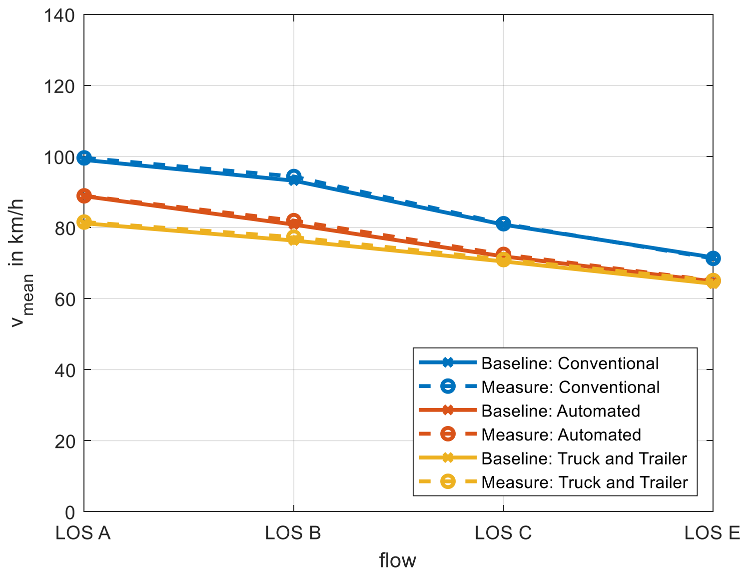


Figure 138. Roadworks zone, Mean speed in Segment 2

Traveltime

Since the mean speed and the traveltime are closely related to each other, the results from traveltime and mean speed is expected and also observed to be similar. As already mentioned, since the VuT is the only vehicle that is affected by the measure, we will see no significant difference in the traveltimes between the baseline and the measure simulation of the overall traffic. But a comparison of Table 44 and Table 45 shows a difference in the traveltime in Segment-2 and segment 3. Due to the upcoming congestion in Segment-2 we can see in Table 44 an increasing trend of the traveltime. But in Table 45 the traveltime is nearly constant due to the limited number of vehicles in this Segment-3.

Additionally, Figures 139 and 140 include the results for the traveltime for Segment-3 and Segment-2, respectively.

Table 43. Roadworks zone, Travel time, Segment 3

		Baseline		Measure	
		Mean	Deviation	Mean	Deviation
		s	s	s	s
LOS A	Conventional	35.77	1.17	35.69	1.17
	Automated	38.75	1.63	38.83	1.67
	Motorcycle	37.61	3.33	37.73	3.33
	Truck	40.63	0.88	40.72	0.91
	Trailer	43.37	0.91	43.29	0.65
LOS B	Conventional	36.04	1.27	35.98	1.31
	Automated	40.09	1.6	39.94	1.65
	Motorcycle	39.58	3.55	40.33	3.29
	Truck	41.62	1.34	41.55	1.19
	Trailer	44.03	0.89	44.07	0.96

LOS C	Conventional	36.63	1.28	36.73	1.3
	Automated	40.21	1.51	40.2	1.51
	Motorcycle	40.91	3.55	40.75	3.84
	Truck	42.11	1.43	42.17	1.38
	Trailer	44.77	1.33	44.76	1.38
LOS E	Conventional	36.85	1.45	36.82	1.4
	Automated	40.13	1.43	40.1	1.45
	Motorcycle	38.84	3.08	39.27	3.31
	Truck	42.66	2.12	42.88	2.24
	Trailer	44.85	1.63	45.06	1.69

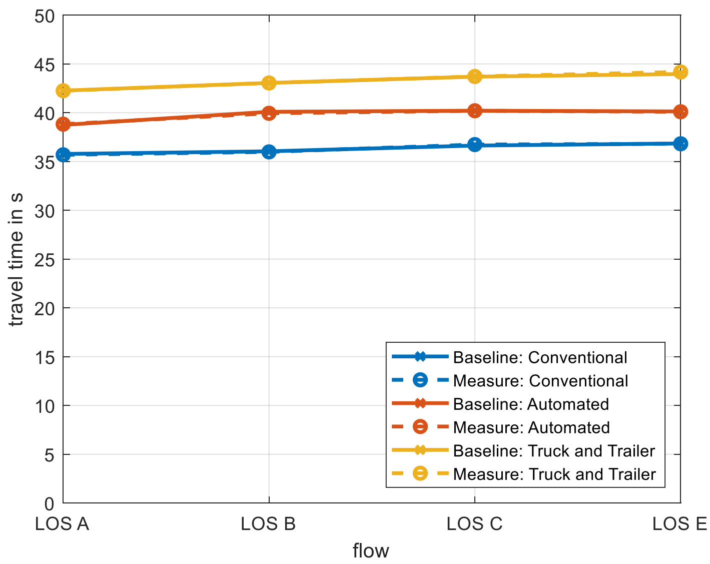


Figure 139. Roadworks zone, Travel time, Segment 3

Table 44. Roadworks zone, Travel time, Segment 2

		Baseline		Measure	
		Mean	Deviation	Mean	Deviation
		s	s	s	s
LOS A	Conventional	35.05	2.69	34.83	2.5
	Automated	39.05	2.93	39.02	2.86
	Motorcycle	35.46	3.49	35.16	2.98
	Truck	41.75	2.99	41.5	1.75
	Trailer	44.49	2.75	44.21	1.12
LOS B	Conventional	37.26	3.1	36.83	2.5
	Automated	42.81	3.27	42.34	3.06
	Motorcycle	41.2	5.33	41.3	4.58
	Truck	44.91	5.3	44.54	3.56
	Trailer	47.96	5.06	47.21	3.14
LOS C	Conventional	42.97	3.47	42.86	3.68
	Automated	49.18	4.46	48.79	4.13
	Motorcycle	46.46	7.53	46.34	7.5

	Truck	51.4	6.02	50.58	5.64
	Trailer	51.23	4.94	50.6	4.76
LOS E	Conventional	46.1	3.15	46.2	3.45
	Automated	51.29	3.79	51.39	3.73
	Motorcycle	48.07	6.94	48.48	6.92
	Truck	56.08	4.89	55.26	4.28
	Trailer	57.22	6.87	56.21	6.37

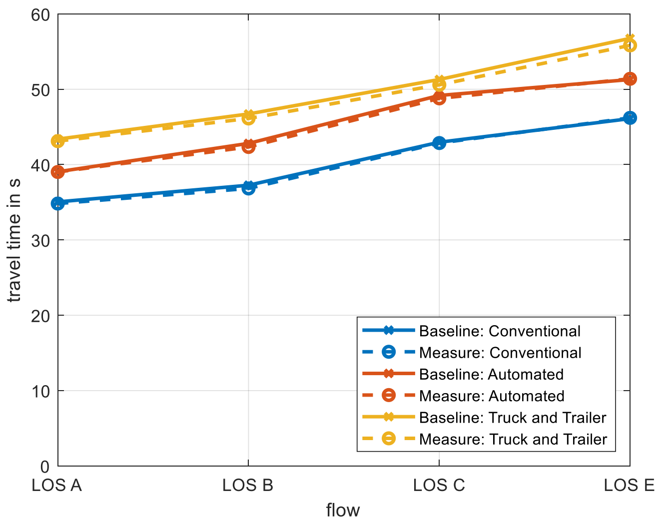


Figure 140. Roadworks zone, Travel time, Segment 2

Time Gap (TGAP)

The minium time gap (TGAP) between two vehicles is a measure of vehicle safety. In the scope of this analysis, TGAP was evaluated segments 2 and 3 for the time frame when the VuT is in the respective segment. If the time gap falls below the threshold of 10 seconds, then TGAP event is recorded. From each of this events then TGAP is evaluated. The minima of these events are taken over a simulation and the result is input to to the histogramm of cumulated 60 simulation runs for each traffic density levels (i.e., from LOS-A upto LOS-E).

In Figure 141 the corresponding TGAP values for the baseline scenario for the Segment-3 (i.e., the roadworks zone) at each LOS level is seen. The consistent increasing trend with increasing traffic density for the 0.5-1 sec TGAP window is clearly observed in this bar-graph. The other TGAP windows have no significant or decisive trend. In Figure 142 the same segment with a measure signal affecting only the VuT is seen. As expected the result are slightly changed (due to the statistical behavior of the traffic) however the overall trend seems to be preserved on the TGAP results.

In Figure 143 we are looking at the baseline situation for the same scenrio, but this time at the Segment-2, which is interesting to look at as the measure signal is transmitted to the VuT in this segment. In this figure it is observed that all the TGAP values are concentrated in the 0-1 sec window. There is also a decreasing trend in the TGAP values 0.5-1 sec with increasing traffic dentsity. In Figure 144 likewise, we show the result for the measure simulations for Segment-2. The increase of occurances of TGAP values in the 0-0.5 sec window is clearly observed.

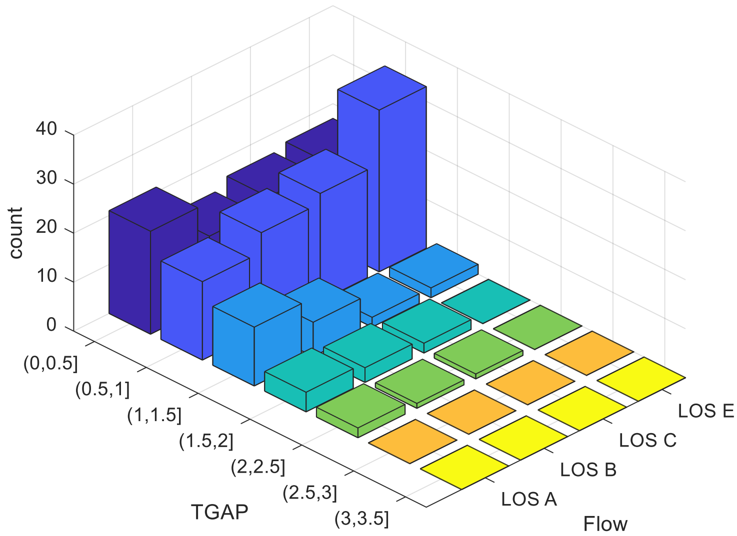


Figure 141. Roadworks zone, Time gap, Baseline, Segment 3

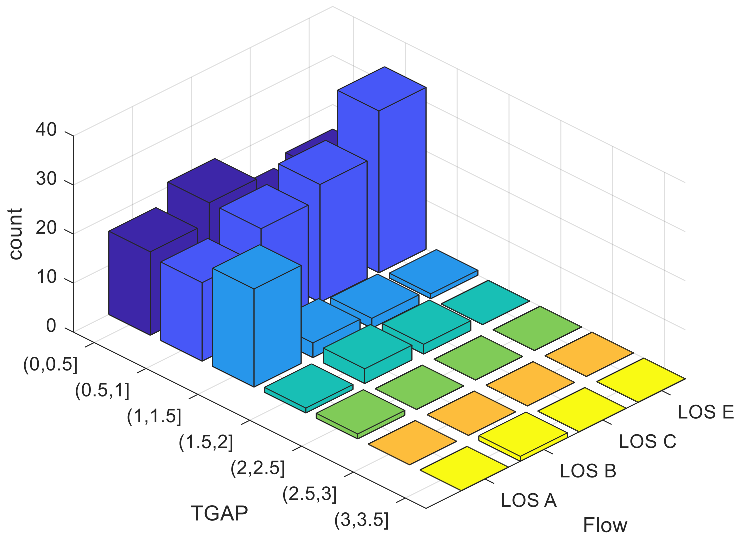


Figure 142. Roadworks zone, Time gap, Measure Segment 3

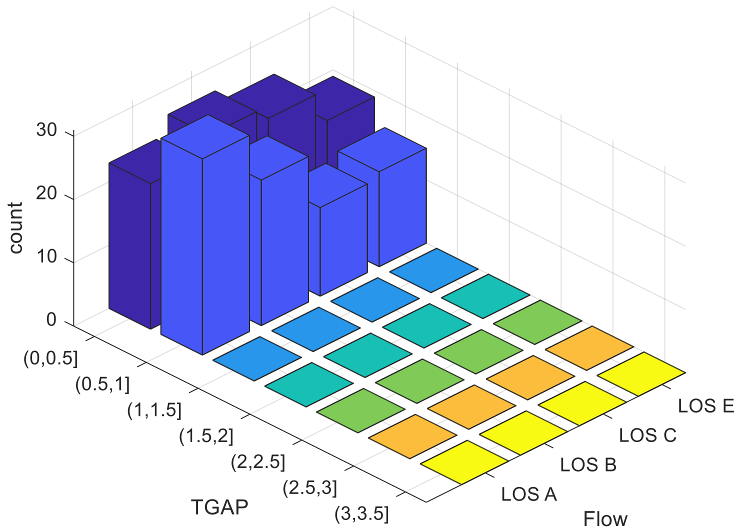


Figure 143. Roadworks zone, Time gap, Baseline, Segment 2

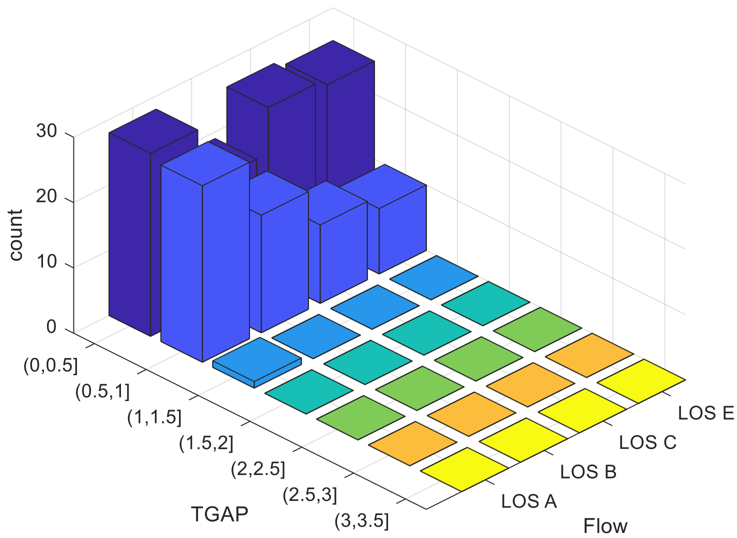


Figure 144. Raodworks zone, Time Gap, Measure, Segment 2

<u>Time to Collision (TTC)</u>

This metric is relevant for analysing safety as it is a measure of the imminence of possible collisions and therefore enabling assessment of critical traffic situations. The following two figure clusters, summarise the cumulative frequency of TTCs for varying traffic densities (i.e. from LOS A upto LOS E). In these plots the TTC variation was plotted for baseline and two measure scenarios for both of the relevance zones, namely for the Segment-3 (Figure 145) and the Segment-2 (Figure 146) we observe that the cumulative frequencies of TTCs in Segment-3 (i.e., roadworks zone region) for all traffic densities, which at the first sight do not seem to be very much affected from baseline values. However, in a close look it is observed that there is a consistent small improvement due to the measure signal on the smaller TTC values, particularly for LOS-B, LOS-C and LOS-E, which is positive. The improvement in TTC for LOS-A is too small in comparison to the other traffic densities. From these plots, it is also seen that TTC values for 5-10 sec window are also consistently higher, which was counter intiutive, yet not a critical development in comparsion to the improvement in the TTC for lower TTC values.

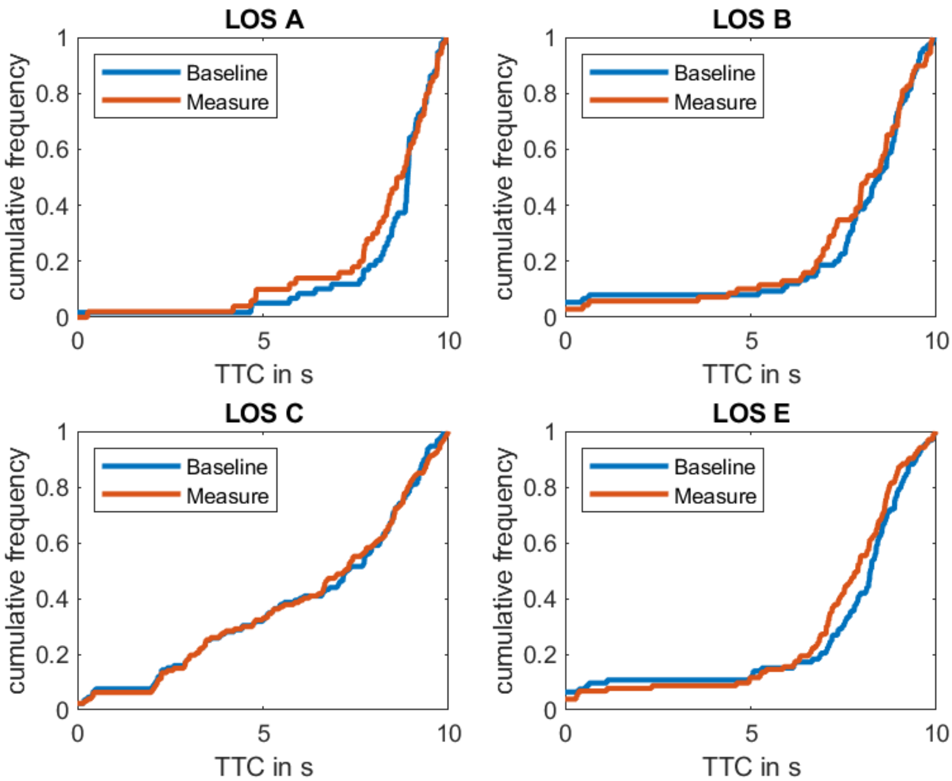


Figure 145. Roadworks zone, TTC, Segment 3

In Figure 146 on the other hand we give the similar TTC comparison for the Segment-2. The difference between the baseline and measure scenarios is significantly less prominent in compasion to the Segment-3, however the improvement for the LOS-A with the measure signal is an interesting result that needs further analysis. This can indicate some alternative upstream control strategies for varying traffic densities. For higher LOS levels, the number of occurances of low TTC values were to small to display a trend or draw a conslusion, further indicating a dedicated in-dept analysis of the issue.

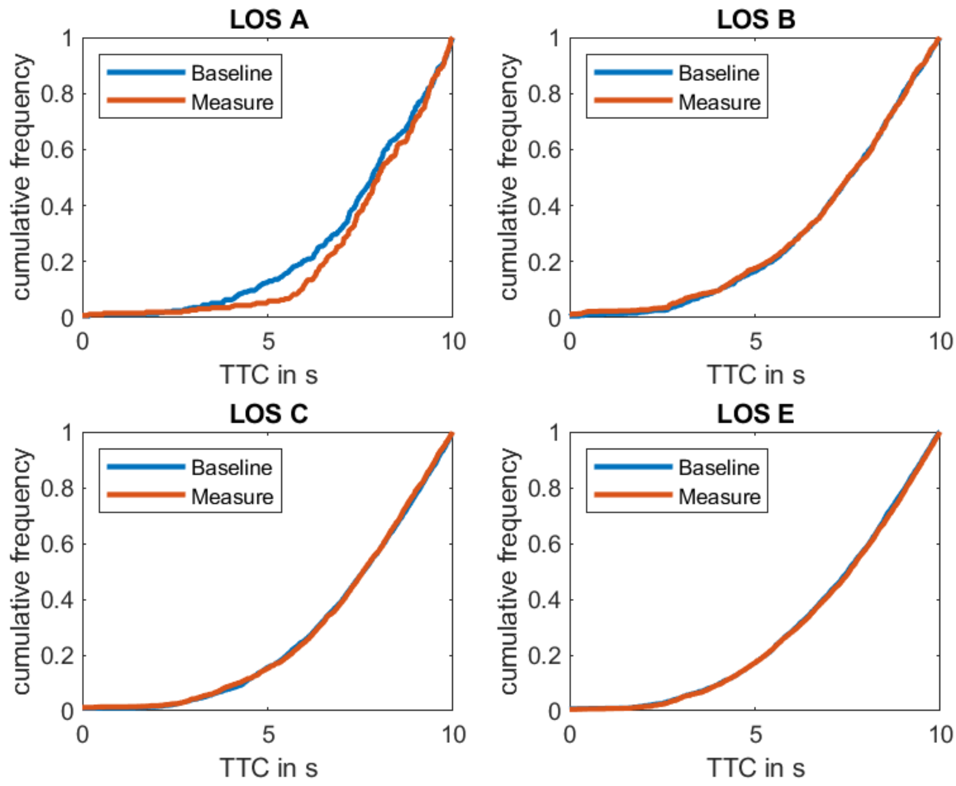


Figure 146. Roadworks zone, TTC, Segment 2

__Number of Vehicles stopped and merge distance__

In this final metric, we look at the occurances of vehicle complete stops as a measure of traffic safety and efficieny to provide a further insight into this scenario. We need to strees out that for each traffic density, a batch of 60 simulations with random seeds is conducted to obtain a statistically sensible result. However we note further that not in all cases of the 60 simulations or experiments the VuT drove on the rightmost lane, which is closed in segment 3 according to the experiment and scenario design criteria. Only vehicles on the rightmost lane at the end of segment 2 are forced to change the lane and merge into the remaing lanes. In Table 46, those cases are listed and broken down into the number of stops and the number of merges. It is obvious from the obtained results that due to the rather small number of occurrances with the VuT driving on the rightmost lane, it as difficult to make a statement or draw a conclusion whether the test was successful or not. In the measure scenario the number of stops is lower, but also the number of merges in comparison to the baseline. Beyond this no further statements could be made based only on the summary of results as presented in Table 46.

Table 45. Roadworks zone, Number of vehicles stopped

	Baseline		Measure	
	Num. stopped	Num. Merged	Num. stopped	Num. merged
LOS A	3	34	0	27
LOS B	3	26	1	4
LOS C	3	26	2	12
LOS E	3	35	2	23

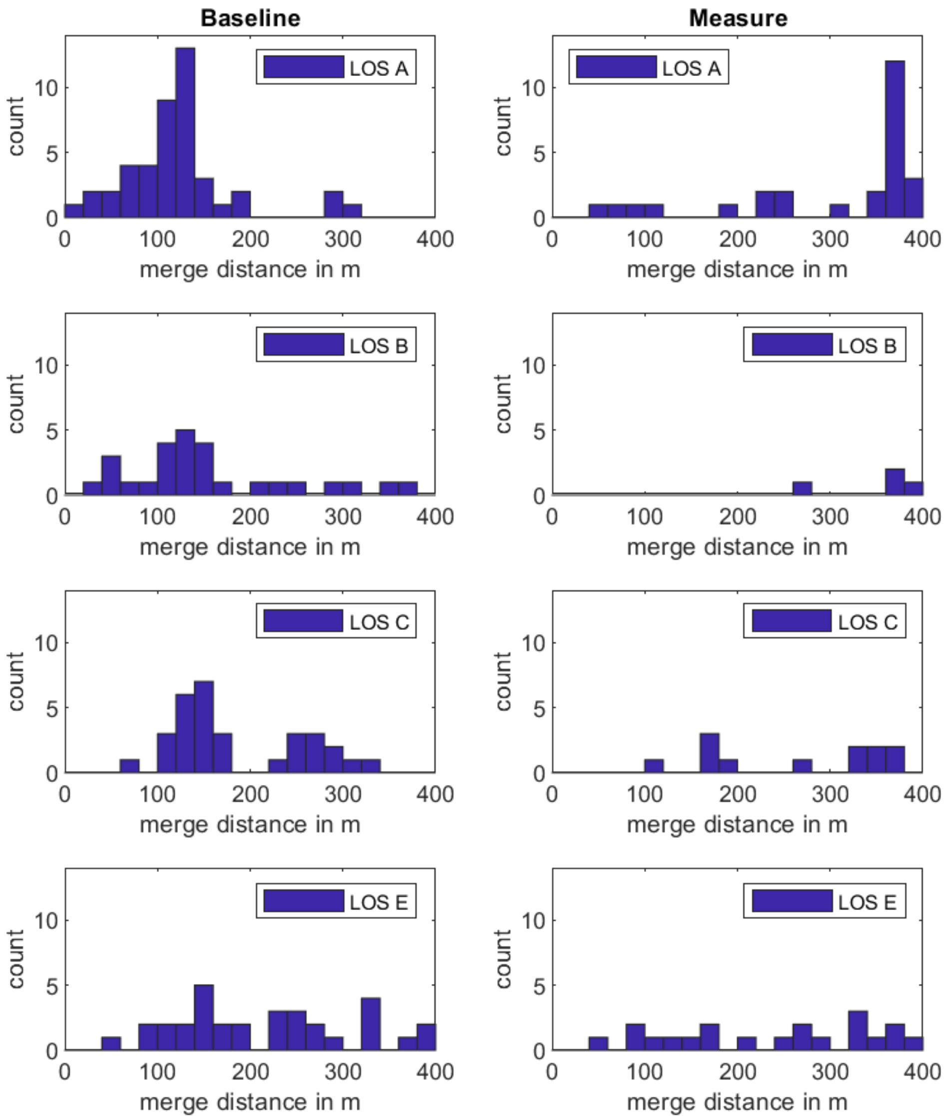


Figure 147. Roadworks zone, Merge distance

In order to provide a further insight, we give in Figure 147 the merge distances of the VuT. We immediately observe that the merge distance is increasing with increasing traffic density for the baseline scenario, seen in the 4 figures on the left hand side, which indicates that the lange is initiated earlier with increasing traffic density. This is result is quite intuitive and matches the expectations. For the measure simulations for the same scenario however, the merge distances appear to spread and increase with increasing traffic density. This is clearly visible for LOS A, however the number of relevant occurrences of small (i.e.,<400m) merge distances were statistically too few, which prevents to make a further and stronger statement.

8. New Safety Criteria

8.1 Non Scenario/UC specific potential of INFRAMIX

The concept of INFRAMIX, with the INFRAMIX message set is much broader than the specific scenarios and use cases. As can be seen in Figure 148 more than 40% of the accidents are "rear end collisions", 18% are rear end collisions onto a standing vehicle. Referring again to the fact, that 75% of accidents are related to inattentiveness/distraction, insufficient safe distance and inadequate choice of speed, it is believed that a pre warning of standing vehicles (see also SC2 for the Road works trailer) or a general warning of congestions ahead could potentially drastically reduce this collision type. If a congestion or any type of standing vehicle is detected timely, potentially most of the rear end collisions onto a standing vehicle and also partly those onto very slow moving vehicles at the end of a queue could be addressed by the "general hazardous" warning tested within the project. This of course also holds true for objects on the road, however they do not hold responsible for large accident numbers.

ASF has a camera coverage of more than 80% (100% in tunnels). Because of the amount of moving cameras on the network at the same time 60% permanent coverage (again 100% in tunnels) is assured at all time. Automated object detection, especially standing objects is already in trial operation. When considering that the most congestion intensive parts of the network (which are also showing the most rear end collisions onto a standing vehicle) could be equipped in the near future, this technology in combination with the "Basic hazardous waring" shows large potential in reducing this type of accident, given a large enough penetration rate of connected vehicles.

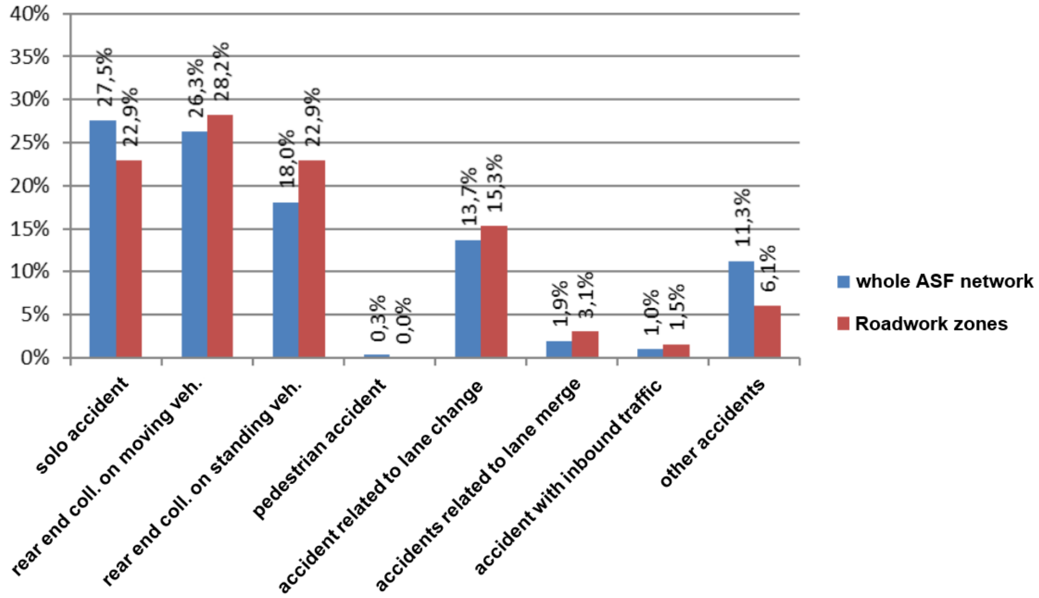


Figure 148. Percentage of accident types on the ASFINAG road network [source: "Unfallgeschehen im ASFINAG-Netz 2018 Wien, Stand 09.07.2019; study conducted on behalf of ASFINAG Service GmbH by KFV Sicherheit-Service GmbH KVI]

8.2 Scenarios specific potential of INFRAMIX:

8.2.1 Scenario 2: Road works zone

Road work zones hold accountable for about 6% of the accidents on the ASFINAG network[4]. However, considering that on average about 3% of the network are typically roadworks zones, RWZ can be considered as more dangerous than the average network. As can be seen in Figure 148, in RWZ more than half of the accidents are rear end collisions onto a standing or moving vehicle. A striking figure highlighting the problem, is that as many 5-10% of roadwork warning trailers were involved in such a collision every year in Austria according to project partner ASF.This is not only costly for the road operators but of course also an important safety concern: Considering that especially during the installation and decommission of a RWZ employees and contractors of the road operators have to work within the zone of danger, just last year one ASFINAG employee was killed in such an accident.

As discussed in the introduction of section 7, approximately 75% of accidents are related to inattentiveness/ distraction, insufficient safe distance and inadequate choice of speed. The road works warning C-ITS message investigated in INFRAMIX has great potential to reduce these types of accident considerably, given a large enough penetration rate of connected vehicles. The additional pre-warning offers the possibility to raise awareness of inattentive drivers and should lead to adequate reduction of speed and increase of safe distance. The new roadworks trailers of ASFINAG will therefore, among other technologies, be equipped with a ITS-G5 unit which is able to send out this pre-warning.

This functionality is going to be very important for future automated vehicles, since a roadwork zone will be one of the typical cases where the human driver will have to take over again. This poses a new safety risk introduced by the new technologies, that was not present up to now. Minimizing the risk by ensuring a large enough transition time for such handover manoeuvres will be a future challenge.

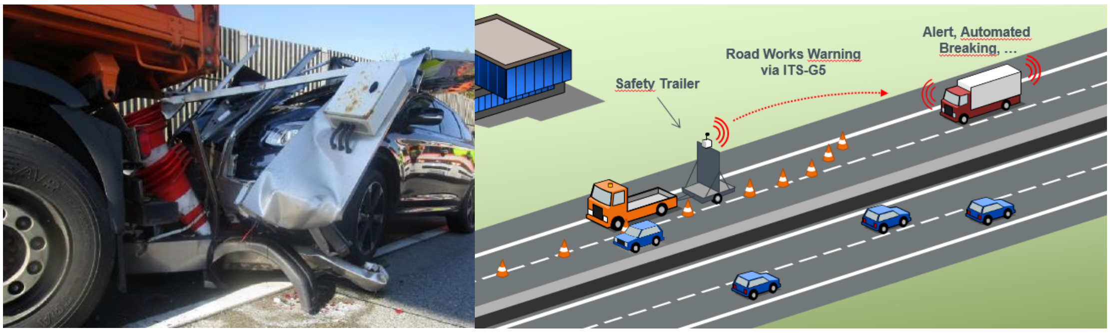


Figure 149. Left: Collision aftermath of a rear end collison onto a safetey trayler. Richt: C-ITS concept for RWZ warning of an intelligent safety trailer sendeing the corrsponding INFRAMIX message

[4] From 2018 on whether or not an accident was related to a road work zone became a mandatory detail in the registration of the accident.

Scenario 1&3 (Dedicated lane and Bottlenecks)

As seen from microscopic simulation results in section 7 the TTCs for the different traffic control strategies do decrease when using those strategies. This is not surprising, but rather a logic necessity, since the purpose of these controllers is to pack more traffic into the same physical space in case of congestions

Above it was shown that the introduction of AVs and the corresponding services addressed in INFRAMIX offer a large potential of addressing more than 40% of typical accidents on the highway. It is beyond of scope of the INFRAMIX project to give a proper estimate on how many of these accidents could be prevented by the suggested measures. However, simulation results in section 7) clearly showed that the introduction of more and more AVs will also require new traffic control strategies for which a deterioration of TTC of a few percent is predicted. The deterioration of TTC in the order of magnitude of 10^-2 seconds (e.g. some tenths of milliseconds) is a small added risk compared to the benefits offered from the new technologies, considering furthermore that such control strategies do by far not come into play constantly, but only for considerably high traffic volumes.

8.3 Possible recommendations to Directive 2008/96/EG and ISO ISO39001

The results and considerations above show th great potential of C-ITS messages for road safety. It was identified that the key points analized within the INFRAMIX project are addressed in both Directive 2008/96/EC and ISO 39001

Directive 2008/96/EC of the European Parliament and of the Council of 19 November 2008 on road infrastructure safety management regulates the introduction and implementation of procedures for impact assessments concerning the road safety, road safety audits, the road network safety management and safety checks by the EU member states.

In the annexes of this directive guidelines and rules for road safety impact assessment for infrastructure projects, road safety audits for infrastructure projects, classification of road sections with a high accident frequency and classification of road network safety, are layed out. Here the consortium identified the lack of menitioning of C-ITS technologies as a weakness of this directive. Unfortunately this analysis was carried out during a time window where the directive was already underfoing a revision and at the end of 2019 a new version of this directive was released by the EC. The new directive comprises considerable changes,but in our opinion still would have benefitet from a clearer mentioning of C-ITS in some sub points of the annexes. However since the directive is just newly released it was refrained to approach the responsible commity on this issue.

ISO39001 [13] on road trafic safety (RTS) management systems – requirements provides guidance for use addresses a similar topic, but on a higher level.

„The requirements in this International Standard include development and implementation of an appropriate RTS policy, development of RTS objectives and action plans, which take into account legal and other requirements to which the organization subscribes, and

information about elements and criteria related to RTS that the organization identifies as those which it can control and those which it can influence."

In subchapter 6.3 of this document "RTS performance factors" such points as for example road design and safe speed, use of appropriate roads, depending on vehicle type, user, type of cargo and equipment; using safe driving fitness of drivers, etc. are addressed. It was identified that C-ITS is not mentioned in this subpoint (or anywhere else in the document), but that this is a point that is clearly missing form the INFRAMIX point of view. This subchapter is closely linked to chaper A6.3 which is defining the pints mentioned in 6.3 in more detail.It is the belief of the INFRAMIX consortium that the ISO39001 would benefit from adding a point, such as "Use of Cooperate Intelligent Transport Systems (C-ITS) for warnings, interoperabilitiy, signage and other traffic information." or similar.

9. Conclusions

In this deliverable we described the obtained results as well as their interpretations as a result of various simulation and testing methodologies that were developed in the scope of the INFRAMIX project. The respective methodologies vary from pure simulation tools implementing microscopic and sub-microscopic modelling of the specific use-cases, mixed-reality approaches (i.e., Hybrid Testing) for combining real life testing with simulation, as well real-life scenario testing on motorways.

In the scope of the INFRAMIX project, the sub-microscopic simulation refers to the complete simulation framework of a single autonomous ego-vehicle with complete authority over the vehicle dynamics, control actuators, surround perception as observed from the simulated sensors and autonomous ADAS functions. Additionally, this definition is the same in the Hybrid Testing framework except for the part that the vehicle dynamics is not simulated but measured and also that the ADAS functions are implemented directly on the vehicle. The Sub-microscopic simulations and Hybrid Testing methodology is used to investigate certain use cases in which the focus was just one automated vehicle, which is the vehicle under test (i.e., VuT), in combination with simulated virtual traffic composing of a mixture of automated and manual driven vehicles at various penetration rates. Therefore, investigations of INFRAMIX scenarios were conducted in the scope of microscopic and sub-microscopic simulation analyses as well as the Hybrid Testing implementation studies for an additional level evaluation. Details about the architecture and software components of the sub-microscopic simulation can be found in the Deliverable "D2.3-Specification of sub-microscopic modelling for intelligent vehicle behaviour", whereas the respective component descriptions and setup of the Hybrid Testing is available in the Deliverable "D4.2-Public demonstration phase and data delivery report". In this scope, many key performance indicators (KPIs) or metrics were defined and analyzed, to investigate, understand and mitigate the efficiency and safety challenges to be expected by the introduction of mixed traffic situations and scenarios. In doing so, the effect of infrastructure signals in the form of C-ITS recommendations, new visual signs, as well as novel traffic control strategies were designed and evaluated and their respective effects on efficiency and safety KPIs were analyzed in the form of "baseline" and "measure" scenario studies.

Based on the obtained results, conducted evaluations and the gained experience, there are clear observations made for the set of methodologies and software tools as well as their capabilities and limitations for analyzing the specified mixed traffic scenarios involving automated and manual driven vehicles. These analyses indicated some obvious implications of the analyzed measures using the conjectured C-ITS messages and the IMC. However, not all the measures and KPIs were effective in analyzing their respective impact on the traffic flow. Also, not every measure was found to be as influential in the same way for every scenario. The overall observation is that the effectiveness of the measure over the baseline traffic flow is quite dependent on the specific scenario, as well as the way and the means that the measure is implemented.

As a result of the sub-microscopic simulation studies and Hybrid testing analyses, the main overall observation is that, the speed recommendation for the connected and automated vehicle traffic have positive implications in terms of safety, whereas the lane change recommendations usually lead to under utilization of traffic flow efficiency and creates risky (in terms of reduced TTC) traffic situations. It needs to be noted further here that the conducted analysis and obtained results indicate the need for many more simulations to provide sufficiently represented statistical distributions. For the specific implementations of sub-microscopic simulations and Hybrid Testing experiments, since the run-time of each scenario was merely restricted to a minute, the occurrence of sufficient examples of the VuT in a specific situation was limited, which results in a slow accumulation of relevant events despite the hundreds of repetitions.

To get a better understanding of the behaviour of mixed traffic on highways, and how mixed traffic can be improved using novel control techniques, extensive evaluations have been performed utilizing microscopic traffic simulations. Various aspects of the scope of the INFRAMIX project have been addressed and studied in great detail. Mixed traffic was modelled in the simulation based on real data for both testsites in Austria and Spain, whereas the main evaluations on traffic efficiency have been performed using the Spanish testsite of AP7 near Girona. Next to the traffic model, many other aspects have been included. The communication between vehicles and road side units was modelled, as well as the road infrastructure including road sensors (for gathering information on vehicles and traffic situation) and variable message signs (for informing vehicles with advices and limits). Furthermore, comprehensive behaviour models for automated and connected vehicles have been included, which implement the reaction on VMS, but also on digital advices (e.g. IVIM) sent out by the road side units. Moreover, a model of the Inframix Management Centre was used, which integrated the real traffic control algorithms in order to improve the efficiency of the traffic by adjusting the speed, the lane change behaviour, and distance and driving behaviour dynamically according to the current traffic situation.

In the simulation, the behaviour patterns formed by thousands of vehicles have been observed and studied. Especially for mixed traffic, where automated and conventional passenger vehicles and Trucks and Trailers are coming together, specific conclusions could be drawn. It can be observed that icreasing the penetration rate of automated vehicles decreases traffic efficiency. This is due to the increased distance behaviour of ADAS functions compared to human drivers and is a well-known fact in the research community. Utilizing the ACC time-gap adaptation controller which reduces these gaps in critical areas for a short period of time, can resolve this issue and increase traffic efficiency over the no-control case by some 50% when it comes to delays, even for a low RSU coverage of the network. On the other hand, having more and more connected vehicles on the road provides various other possibilities to improve traffic efficiency. Whereas conventional vehicles can only be addressed with advices in a conventional way, e.g. by implementing and controlling variable message signs, connected vehicles can receive specific advices via ITS-G5 or cellular links (e.g. LTE or 4G/5G) communication technologies.

The main conclusion of the evaluations is that the employment of the developed traffic controllers leads to improvement of traffic efficiency. Giving speed limit advices to conventional vehicles via VMS and to connected/automated vehicles additionally via communication already achieved a decrease of delay times by 10 to 15%. With further communication and automation, additional techniques to control the traffic can be used in order to improve traffic efficiency even more. For example, the efficiency could be improved by up to 50% in our experiments compared to an uncontrolled case, when using intelligent time-gap adaption controllers in the traffic management.

With the rationale in mind of avoiding expensive infrastructure investments for deploying VMS in close intervals, solutions were analysed which would require less VMS and even no VMS at all, while relying on communicated traffic advice. In these cases, the previously found efficiency values could be achieved with a penetration rate of communication capable vehicles (connected and automated ones) of 15 - 20% or more. It confirms that sending advices to just a portion of vehicles is sufficient because they influence the whole traffic due to their adapted speed behaviour. A final evaluation goal compared ITS-G5 and cellular services, which are equally qualified for communicating the analysed traffic control messages.

Next to efficiency improvements gained by the controllers, the safety of the vehicles should not suffer significantly. In this regard, all microscopic evaluations performed in the scope of INFRAMIX have always included an analysis of traffic safety. In this analysis, the time-to-collision metric (TTC) has been observed. The TTC analysis presents more a potentially increased risk of accidents than actually happening accidents themselves. The results showed that an improvement of traffic efficiency always comes with a minor deterioration regarding the TTC. However, this deterioration (<1% in average) is mostly related to the fact that a traffic system with fewer congestion and higher speeds is naturally accompanied with smaller TTC values (e.g. even in the situation of higher speeds at equally large safety gaps). From our point of view, this potentially minor deterioration in traffic safety is acceptable with the great improvement achieved in traffic efficiency thanks to the control mechanisms.

The possible safety impact of the INFRAMIX approach is much broader than the 3 scenarios discussed. Because 75% of accidents are related to carelessness, distraction, insufficient safe distance and inadequate choice of speed, it is believed that a pre-warning of standing vehicles (see also SC2 for the Road works trailer) or a general warning of congestions ahead, could drastically reduce these collision types.

Concerning the impact of Dynamic Lane Assignment on traffic efficiency, the effect is positive for AVs, especially when the demand for traffic is scaled down to 60% and the penetration of AVs is 25%, but not for the rest of the traffic. If areas around on / off ramps are included in the assignment logic, the results are a little bit higher than the other case. The analyzed KPIs showed neither an improvement in throughput nor in TTC.(time to collision – used for safety analysis). KPIs such as the delay time or total travel time decreased significantly, while TTC deterioration was about twice as high as for the bottleneck simulations. Therefore the DLA does not seam an appropriate measure for mixed traffic control.

Finally, results have been presented for the evaluation of estimators under mixed traffic conditions for a) the cross-lane case; and b) the per-lane case. Based on these results, we can conclude that the developed tool for the cross-lane case has reached maturity allowing for immediate exploitation and can provide a necessary basis for real-time control tasks with various requirements regarding the estimation granularity, the estimated variables or the underlying architecture.

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