D4.2

Preliminary simulation and assessment of enhanced traffic management measures

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Dissemination level:

■ PU: Public

- RE: Restricted to a group specified by the consortium (including the Commission Services)
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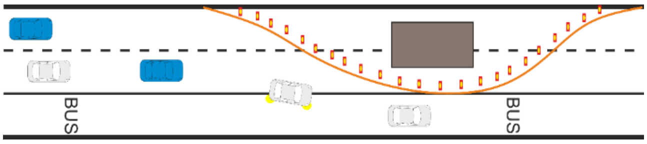
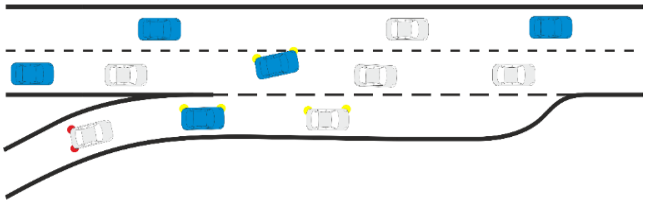
1 Executive summary

Within TransAID we defined five different use cases, during the first iteration, where disruptions of traffic flow are expected to be most severe as a result of transition between automation levels (see also Deliverables from WP2 and WP3). The initially selected use cases were:

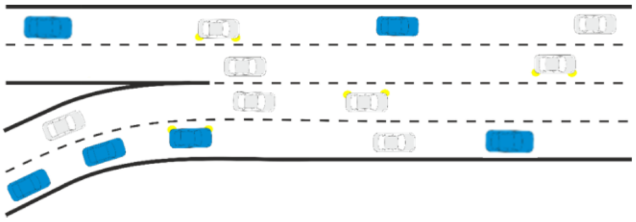
- Service 1 (Use case 1.1): Prevent ToC/MRM by providing vehicle path information



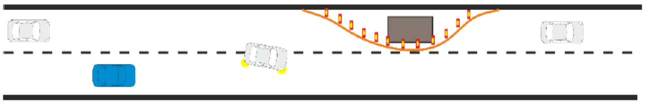
- Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice



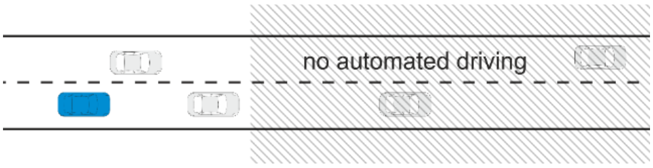
- Service 3 (Use case 3.1): Prevent ToC/MRM by traffic separation



- Service 4 (Use case 4.2): Manage MRM by guidance to safe spot (urban & motorway)



- Service 5 (Use case 5.1): Distribute ToC/MRM by scheduling ToCs



The initial proof-of-concepts of traffic management measures were implemented using the SUMO microscopic traffic simulator for a realistic representation of traffic, and the Python programming environment to code the traffic management procedures. They are calibrated and validated using predefined sets of KPIs/metrics. For each use case, we compare the cases with and without (i.e. base line) active traffic management measures. They are evaluated on their impacts on traffic efficiency (network-wide in terms of average speeds and throughput, and local in terms of tempo-spatial diagrams), traffic safety (by means of the number of events where a time-to-collision lower than 3 seconds occurred), and the environmental impacts (considering CO_2 emissions as calculated by SUMO's PHEMlight emissions model).

- In the first service, path information was provided to AVs to circumvent road works via a bus lane. Simulation results indicated that overall traffic efficiency and CO_2 emissions remained unchanged, while traffic safety was improved significantly. Safety critical events were reduced ranging from 45% to 70%, depending on the level of service and traffic composition. The reduction was larger in case of less traffic and more AVs.

- The second service was applied to a motorway merge area where AVs are given speed advice to merge onto the motorway. The service slightly increased average network speed and slightly decreased CO_2 emissions, especially in case of higher demand (LOS C). The impact on safety was more pronounced with a reduction of critical events around 75%.

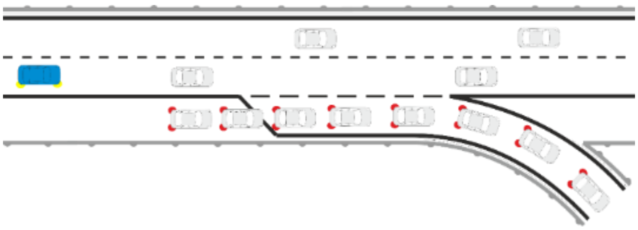
- The third service was applied to a merging situation where two two-lane motorways merge into one four-lane motorway. The idea is to harmonise traffic by assigning the outer lanes to AVs, thereby reducing close interactions between non-automated vehicles and AVs in the merging area. Only in case of higher shares of AVs (> 25% level 2, > 25% level 3) in combination with LOS B or C, improvements were observed in throughput at the cost of slightly lower average network speeds and a decrease in safety. In short, rearranging traffic to dedicated lanes shows largely similar performance to 'uncontrolled merging' (i.e. no measures). However, we hypothesise that separating traffic can outperform uncontrolled merging when cooperative manoeuvring is applied.

- For Service 4 both an urban and motorway scenario were studied with similar network layouts. On a two-lane road we created safe spots upstream of a road works zone on the left lane for AVs to stop in case they reach the limit of their operational design domain. In this case the open right lane remains unblocked. As expected, traffic, safety and environmental benefits are realised. Only in case of congestion, when traffic is already moving slowly, the improvement diminishes.

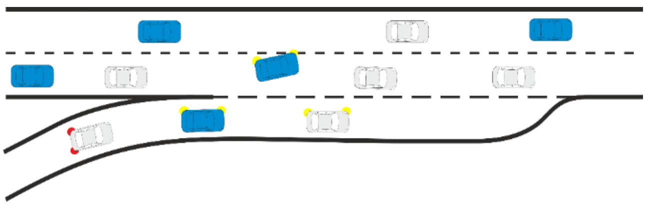
- Finally, a no automated driving zone was simulated along the downstream part of a two-lane motorway for the fifth service. The zone can represent different situations (e.g., road works, geofences, weather, accidents, …) that prevent AVs from staying in automated driving mode. It is assumed that AVs increase their headway before handing over control to the driver. When this happens in a concentrated fashion just before the no-AD zone, traffic flow is impacted. We therefore distribute these handovers in time and space upstream of the zone. It was found that this service greatly smoothens out the disturbances caused by the handovers and improves traffic efficiency.

As explained in Deliverabe 2.2, we used the insights obtained during the first iteration to select five new use cases for the second iteration, adding new functionalities and providing overall improvements and/or extensions regarding vehicle modelling and cooperation. The newly selected use cases were:

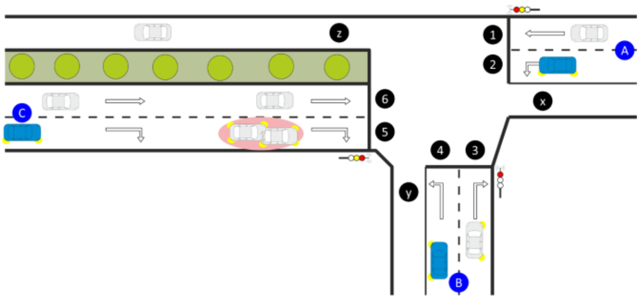
- Service 1 (Use case 1.3): Queue spillback at exit ramp



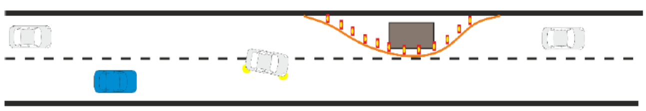
- Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice



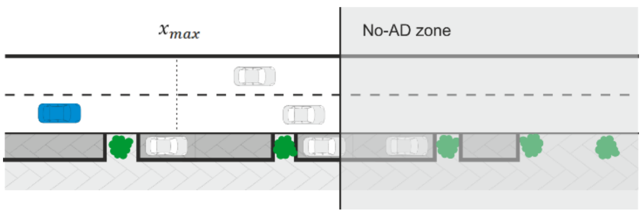
- Service 2 (Use case 2.3): Intersection handling due to incident



- Service 4 (Use case 4.2): Safe spot in lane of blockage & Lane change Assistant



- Service 4+5 (Use cases 4.1 and 5.1): Distributed safe spots along an urban corridor



From our simulation experiments here in WP4, we obtained the following insights for the newly addressed use cases:

- In the first use case (queue spillback at exit ramp), the simulations with traffic management show a significant reduction of the queuing, especially on the main road. This has a beneficial effect on all indicators. The average travel time decreases, despite the speed limits applied in the traffic management scenario. The impact on the average travel time due to the extra capacity generated by opening the emergency lane for queuing exceeds the increase caused by the speed limits. The number of lane changes reduces as the LOS increases, the vehicle mix does not impact the number of lane changes significantly. The number of lane changes only slightly decreases from the baseline to the traffic management scenario. The throughput increases strongly between LOS B and LOS C in the traffic management scenario. There is no significant impact of the vehicle mix on the throughput. Compared to the baseline, the scenario with traffic management has a slightly higher throughput, especially for LOS C and LOS D. The average number of safety-critical events increases with the LOS and with the share of AVs in the vehicle mix, but it is still significantly reduced compare to the baseline. As LOS increases, queue length grows, and therefore speed differences and the occurrence of critical events both increase. AVs that can not find an appropriate gap in the queue to merge can stop on the main route for up to 10 seconds until they finally merge or finally reroute. These vehicles cause perturbations on the lanes of the main road, which can cause TTCs. CO_2 emissions increase slightly with the LOS and with the share of AVs in the vehicle mix. The queue length increases as the share of AVs increases in the vehicle mix. The CO_2 emissions correlate with the queue length, due to stop-and-go traffic in the queues.

- For the second use case (preventing a ToC/MRM by providing speed, headway, and/or lane advice), we noticed that the inclusion of ramp metering (using the merging assistant system algorithm) improved the ToC percentage by means of gap searching, speed advice, and gap creating via pairing. In addition, the number of lane changes also decreased under the control logic as well as the variations between runs, showing improvement on homogeneity of traffic flow. There was a slightly negative impact of traffic efficiency and environmental impact, which could be correlated to the parameter settings of the merging assistant system and ramp metering configuration. The control logic has strengthened safety objectives as one would expect. Less late merging and no end-of-the-acceleration-lane merging will happen, which could cost the performance of average travel time and average network speed, especially under heavier traffic demand due to lower capacity of the on-ramp. Thus, the merging assistant system and the intelligent ramp metering using this system shows the functional ability to prevent ToC and MRM. The trade-off between efficiency and ToC percentage is as expected for non-congested traffic situations. For congested traffic situations, ramp metering targeting lower ToC rates is not effective anymore because of expected increasing ToCs and MRMs of merging vehicles.

- Looking at the third use case (intersection handling due to incident), we assumed that CAVs and CVs receive information about the incident itself (position, type, etc.), and will also receive a reduced speed advice and are able to use another lane to turn right. Due to an update timing plan where the traffic coming from the incident road gets extra green time, the saturation and travel times in the traffic management scenario are up until LOS D. In the LOS D simulations, the building up of the queue is more persistent en precedes downstream in time. The impact of the incident is nevertheless less severe in comparison to the Day 1 C-ITS simulations.

- In the fourth use case (safe spot in lane of blockage & lane change assistant), the simulation results for both the urban and motorway networks indicate that infrastructure-assisted traffic management and cooperative driving can generate traffic efficiency, traffic safety, and environmental benefits in the vicinity of Transitions Areas. CAV guidance to safe spots, lane advice (change/keep) provision from the RSI, and distributed cooperative manoeuvring reduce traffic disruption induced by MRMs in lane, dynamic TORs and non-homogeneous lane change behaviour in the proximity of lane drop bottlenecks (e.g., work zones). Specifically, reported results show that average travel time, shockwaves, lane change intensity, TORs, safety critical events, and CO_2 emissions reduce for Traffic Management scenarios, while throughput increases.

- Finally, the last combination of use cases (distributed safe spots along an urban corridor) showed that the introduction of the proposed traffic management logic achieves overall improvements regarding all KPIs. With respect to the nature of the overall behaviour of this use case with spontaneous parking activities and serve MRM maneuvers, the enhancements, brought by Service 4, have great impact on the traffic system, which ultimately shows in the KPI traffic safety. Due to the adjustment of TOC lead times, more MRM maneuvers appear in the traffic management case. Moreover, the main objective of the current safe spot assignment logic is to provide the best suitable safe spot target given CAV's position, the current traffic state, and parking space availability. A free safe spot cannot be guaranteed in any case. Therefore some MRMs still occur on the road not only due to the capacity limitation of the safe spots, but also due to spontaneous real- life parking behaviour. In conclusion, Service 4 in combination with Service 5 greatly improves the performances of all KPIs with the significant contribution of the safe spot assignment especially in regard of traffic safety, whereas Service 5 expectedly has proportionally greater impact on traffic efficiency and emissions as already indicated in the first iteration for simulations of use case 5.

We finally also provide a short description of how the output of this deliverable feeds into the next one (D4.3) and the integration work in WP6.

2 Introduction

In the following sections, we first give a concise overview of the TransAID project, then highlight the purpose of this document, and finally present its structure.

2.1 About TransAID

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

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

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

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

Iterative project approach

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

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

2.2 Purpose of this document

In this document we elaborate on ten of the previously selected use cases with respect to traffic management of automated driving at Transition Areas. To that end, the scenarios based on the use cases proposed by WP2 are used and adapted to consider various levels of scenario parameters (e.g., penetration of automation technology, traffic demand levels, and the lengths of the Transition Areas). The traffic management procedures developed in Task 4.1 are then implemented within the SUMO simulation environment. At this stage, we bypass the detailed communication processing, and instead rely on basic (less complex) V2X interactions. This allows the execution of various simulation runs and a rapid prototyping.

The results of simulations are assessed by the safety, efficiency, and environmental indicators implemented in WP3. Based on these assessments, the traffic management services are analysed with respect to their performances at Transition Areas. In the next step, these traffic management procedures will be provided/exported as input to WP6, in which a more accurate evaluation is done by taking into account a realistic simulation of the communication processes using the entire simulation framework of iTETRIS and the iCS.

2.3 Structure of this document

This document follows a straightforward structure, in that we discuss each of the ten selected traffic management services in turn in Section 3, as follows:

- First iteration:
  - Service 1 (Use case 1.1): Prevent ToC/MRM by providing vehicle path information
  - Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice
  - Service 3 (Use case 3.1): Prevent ToC/MRM by traffic separation
  - Service 4 (Use case 4.2): Manage MRM by guidance to safe spot (urban & motorway)
  - Service 5 (Use case 5.1): Distribute ToC/MRM by scheduling ToCs
- Second iteration:
  - Service 1 (Use case 1.3): Queue spillback at exit ramp
  - Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice
  - Service 2 (Use case 2.3): Intersection handling due to incident
  - Service 4 (Use case 4.2): Safe spot in lane of blockage & Lane change Assistant
  - Service 4 + Service 5 (Use cases 4.1 + 5.1 (4.1-5)): Distributed safe spots along an urban corridor

For each service we provide an introduction, a detailed description of the traffic management setup (including the modifications, if any, to the baseline), an assessment of the results (i.e. impacts on efficiency, safety, and the environment), and a final discussion.

The document further describes in Section 4 concisely description of how the output of this deliverable will feed into the next one (D4.3) and the integration work in WP6. Final conclusions are provided in Section 5.

2.4 Glossary

ACC	Adaptive cruise control
AV	Automated vehicle
C-ITS	Cooperative Intelligent transportation systems
CACC	Cooperative adaptive cruise control
CAV	Cooperative automated vehicle
CV	Cooperative vehicle
FIFO	First-in, first-out
FMP	First merge point
GUI	Graphical user interface
HAV	Highly-automated vehicles
iCS	iTETRIS control system
ITS	Intelligent transportation systems
(K)PI	(Key) performance indicator
LDP	Lane drop point
LMP	Last merge point
LOS	Level of service
LV	Legacy vehicle
MA	Merge area
MDP	Merge decision point
MRM	Minimum-risk manoeuvre
MS	Merging sequence
MSE	Moderate safety and efficiency
MRM-Z	Minimum-Risk Manoeuvre Zone
NAD	No automated driving

O-D	Origin-destination
RSU	Road-side unit
SAE	Society of Automotive Engineers
SUMO	Simulation of Urban Mobility
TA	Transition area
TLC	Traffic light controller
TM	Traffic management
TMA	Traffic management area
TMC	Traffic management centre
TMNA	Traffic monitoring area
ToC	Transition of control
TOR	Take-over request
TransAID	Transition Areas for Infrastructure-Assisted Driving
TSA	Traffic separation area
TSP	Traffic separation policy
TTC	Time-to-collision
V2X	Vehicle-to-anything
VMS	Variable message sign

3 Traffic management measures per use case

In the following sections we give detailed descriptions of each of the ten chosen use cases for the first and second iteration. For each use, we discuss in turn:

- Introduction
- Traffic management setup
- Results (i.e. impacts on efficiency, safety, and the environment)
- Discussion

3.1 First iteration

3.1.1 Service 1 (use case 1.1): Prevent ToC/MRM by providing vehicle path information

3.1.1.1 Introduction

In this scenario, there are road works on a three-lane urban road as defined in Deliverable D2.2. Due to the resulting road closure, vehicles are by law temporarily allowed to use the bus lane around the work zone (see Figure 1). Such changes in road usage may lead to C(A)Vs not detecting the situation properly, resulting in the need to take a ToC/MRM action. In order to keep traffic flowing smoothly, the TMC can assist these C(A)Vs in planning their path around the obstacle. This is done by providing the path information, allowing the use of the bus lane by the respective C(A)Vs at the adequate road section. A ToC/MRM action due to incomplete information regarding a possible route continuation can therefore be avoided for many C(A)Vs. Some may still perform a ToC due to different reasons and concerns, such as not receiving or unable to process the path information, or if the driver wants to take over. LVs will still receive the path information via conventional signalling.

Moreover, the TMC advises C(A)Vs to operate with increased headways close to the merging section if vehicles are present on adjacent lanes. After passing the merge area, vehicles' gaps are no longer under control of the TMC.

The detailed network configuration for use case 1.1 is summarised in Table 23 of Deliverable D3.1.

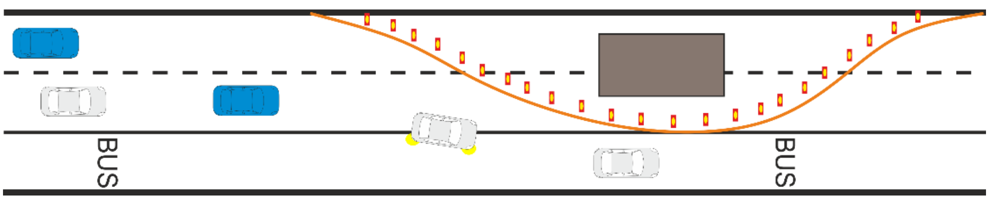


Figure 1: Scenario layout of use case 1.1.

3.1.1.2 Traffic management setup

3.1.1.2.1 Traffic management logic

The flow chart in Figure 2 illustrates Service 1 traffic management logic. The TMC regularly sends the path information to the C(A)Vs entering the covered area, so that they are informed about the possibility to use the bus lane. C(A)Vs will then adjust their paths and use the updated optimal lanes, which correspond to the current traffic conditions. When C(A)Vs enter the merge area, the TMC checks if there are vehicles in the lane adjacent to the C(A)Vs. If this is the case, the respective C(A)Vs are advised to enlarge their headways via the open-gap function[1]. After passing the merge area, the TMC will advise all C(A)Vs to reset their headways according to their vehicle types.

On the C(A)Vs' side, a ToC action will be taken if they do not receive the path information and the predefined threshold distance between to the obstacle is reached. Such C(A)Vs will then operate as LVs in the work zone. Furthermore, it is possible that C(A)Vs will issue a TOR if they cannot process the information successfully, i.e. if they are not technically equipped for the reception of the corresponding message protocols. The remaining C(A)Vs will take the processed path information into account in their individual path planning and pass the work zone in automated mode.

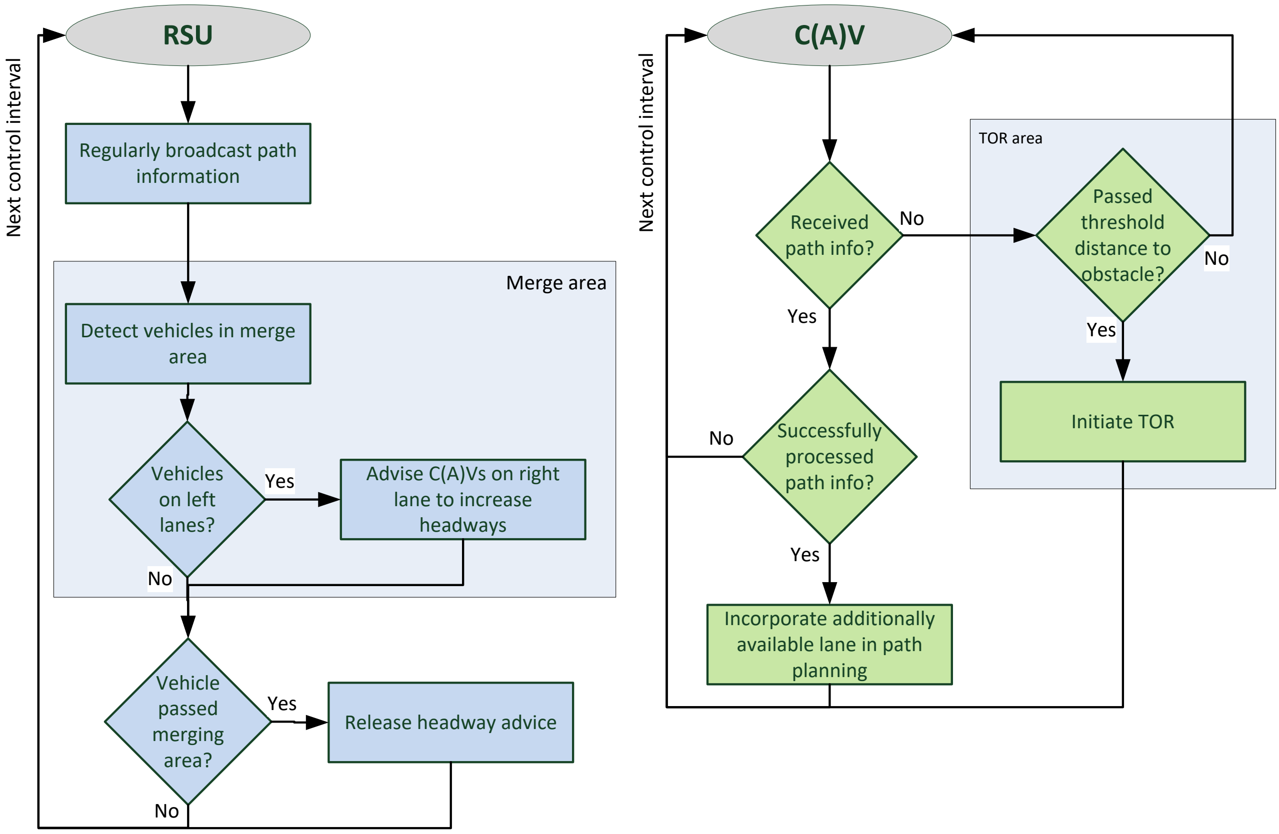


Figure 2: Traffic management logic of Service 1.

[1] This is an interface that TransAID created for the SUMO simulator.

Five parameters need to be defined for adjusting the smoothness degree of traffic operation and vehicle merging behaviour in the open-gap function. Table 1 shows the relevant values in this scenario and the explanation of each parameter.

Table 1: Parameters used in the open-gap function.

Parameter	Used value	Description
newTimeHeadway	4 s	The vehicle's desired time headway will be changed to the given new value with use of the given change rate.
newSpaceHeadway	5 min	The vehicle is commanded to keep the increased headway for the given duration once its target value is attained.
duration	5 s	The time period in which the time and space headways will be changed to the given new values.
changeRate	0.5	The rate at which the new headways' effectiveness is gradually increased.
maxDecel	1 m/s^2	The maximal value for the deceleration employed to establish the desired new headways.

3.1.1.2.2 CAV behaviour

When a C(A)V has entered the information transmission zone, it will process the path information obtained from the TMC. Once its path planning is updated, the C(A)V will try to perform lane-changing manoeuvres to use the rightmost bus lane as soon as possible according to its position and its surrounding traffic situation. Therefore more free space gets available on the adjacent lanes for LVs and C(A)Vs which do not successfully process the path information. The latter ones will undertake a ToC action when they reach the critical distance up to the work zone, and then continue as LVs until they pass the complete work zone.

A C(A)V on the bus lane approaching the merge zone will start to check if there are vehicles on its left-hand adjacent lane. If this is the case, the C(A)V will execute the open-gap function to enlarge its headway, so that its neighbour vehicles can merge into the target lane. After passing the merge area all C(A)Vs continue with their default headway settings.

3.1.1.2.3 Baseline scenario adaptation

Most of the settings in this scenario correspond to those in the baseline scenario except the ToC probability, which is used to reflect an assumed efficacy of Service 1: the lower the ToC probability, the higher the efficacy of Service 1. In the baseline simulation the ToC probability has been set to 75% for C(A)Vs, assuming that 25% of the CAVs will be able to pass the work zone without supplying additional information. For assessing the performance of Service 1 the ToC probability is assumed to be lowered to 25%. That is two thirds of the CAVs which could not pass the obstacle on their own in the baseline are assumed to be affected positively by Service 1 and do not need to perform a ToC. The remaining 25% of CAVs, which perform a ToC, are included with the consideration of possible deficiencies that cause the impracticability of Service 1, such as information processing failures.

In order to understand traffic flow dynamics we deployed detectors on each lane of the road section close to the merge area. The detected vehicle data will be used to decide whether or not the open-gap function should be applied. All simulation settings for Service 1 are recapitulated in the tables in the Appendix in Section 5. For each scenario (LOS and vehicle mix combination) 10 runs with different random seeds are executed.

3.1.1.3 Results

The performance of the proposed Service 1 is evaluated with respect to three aspects, i.e. traffic efficiency, traffic safety, and CO_2 emissions. The simulation results of the baseline simulations are used as reference for the performance evaluation.

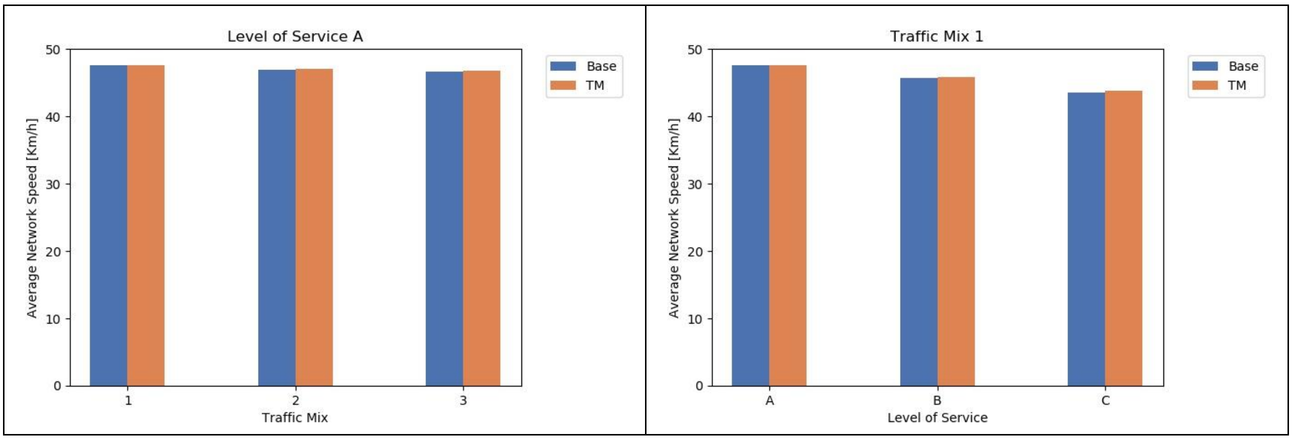
3.1.1.3.1 Impacts on traffic efficiency

Network-wide impacts

Figure 3 shows the average network speed for different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and traffic management service (note that the scaling of the average speed is not equal for every chart).

The results indicate that the introduction of Service 1 does not have much impact on the overall average speed, especially when the traffic state is at LOS A or B. The average speed is around 48 km/h where the allowed travelling speed is 50 km/h.

When the traffic state reaches LOS C and more than 50% of vehicles are C(A)Vs, i.e. vehicle mixes 2 and 3, the overall speed average drops slightly. This is mainly due to the lower travelling speed for a longer duration around the merge area, caused by the introduced open-gap function for C(A)Vs. Nevertheless the speed average is still over 40 km/h. The respective speed difference is marginal. No significant impact is caused by Service 1.



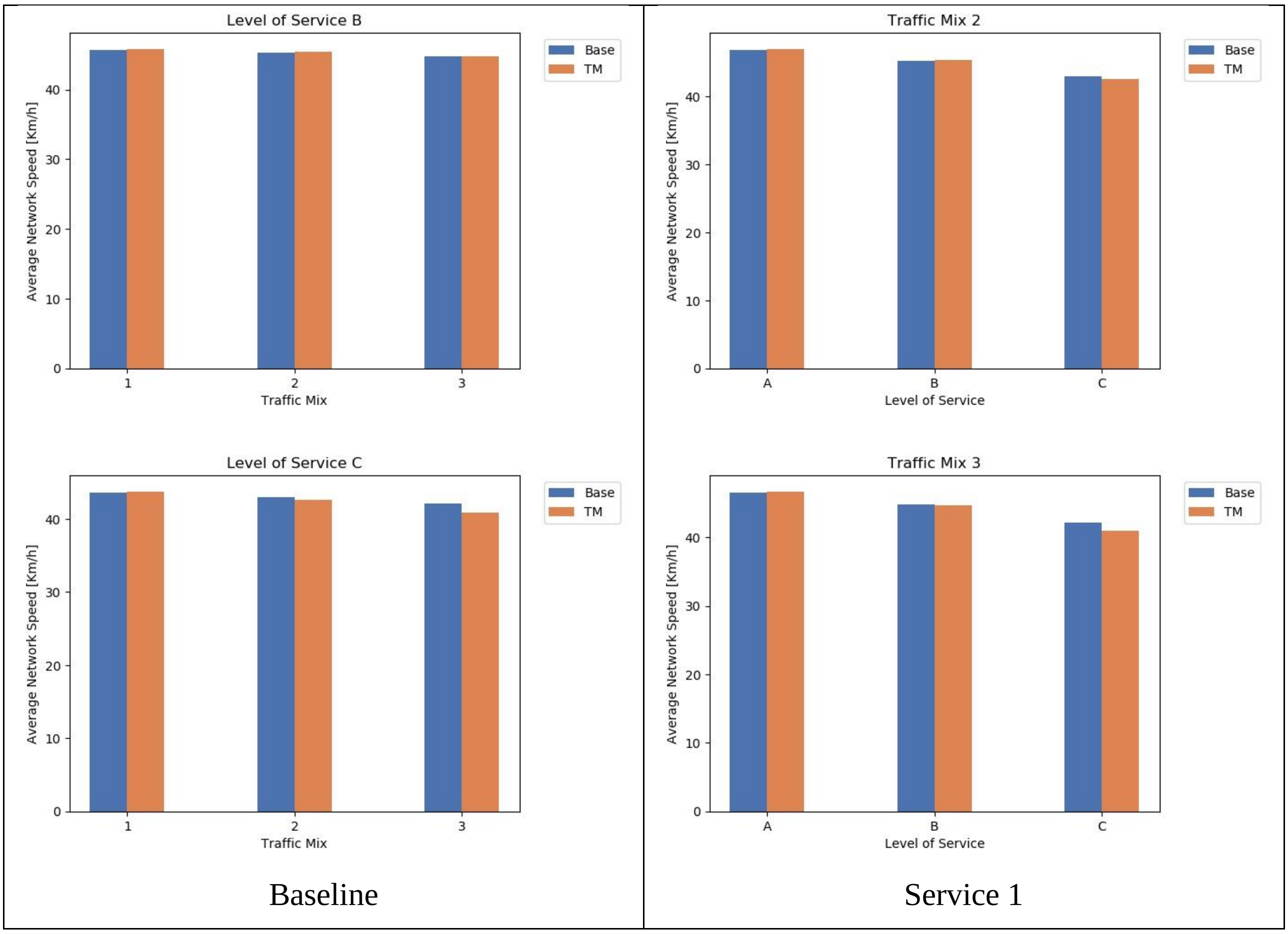


Figure 3: Average network speed for use case 1.1 (urban network) simulation experiments (varying the LOS and vehicle mix). Different bar colours correspond to baseline and traffic management simulations.

Figure 4 shows the throughput for different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and traffic management service (note that the scaling of the throughput is not equal for every chart).

As implied by the insignificant impacts on speed and, more importantly, local flow, Service 1 also does not have a noticeable impact on the overall throughput as well. As indicated in Figure 4, the throughputs at all levels of service with all vehicle mixes in the traffic managed case remain almost identical to the throughputs observed in baseline simulation, i.e. without Service 1.

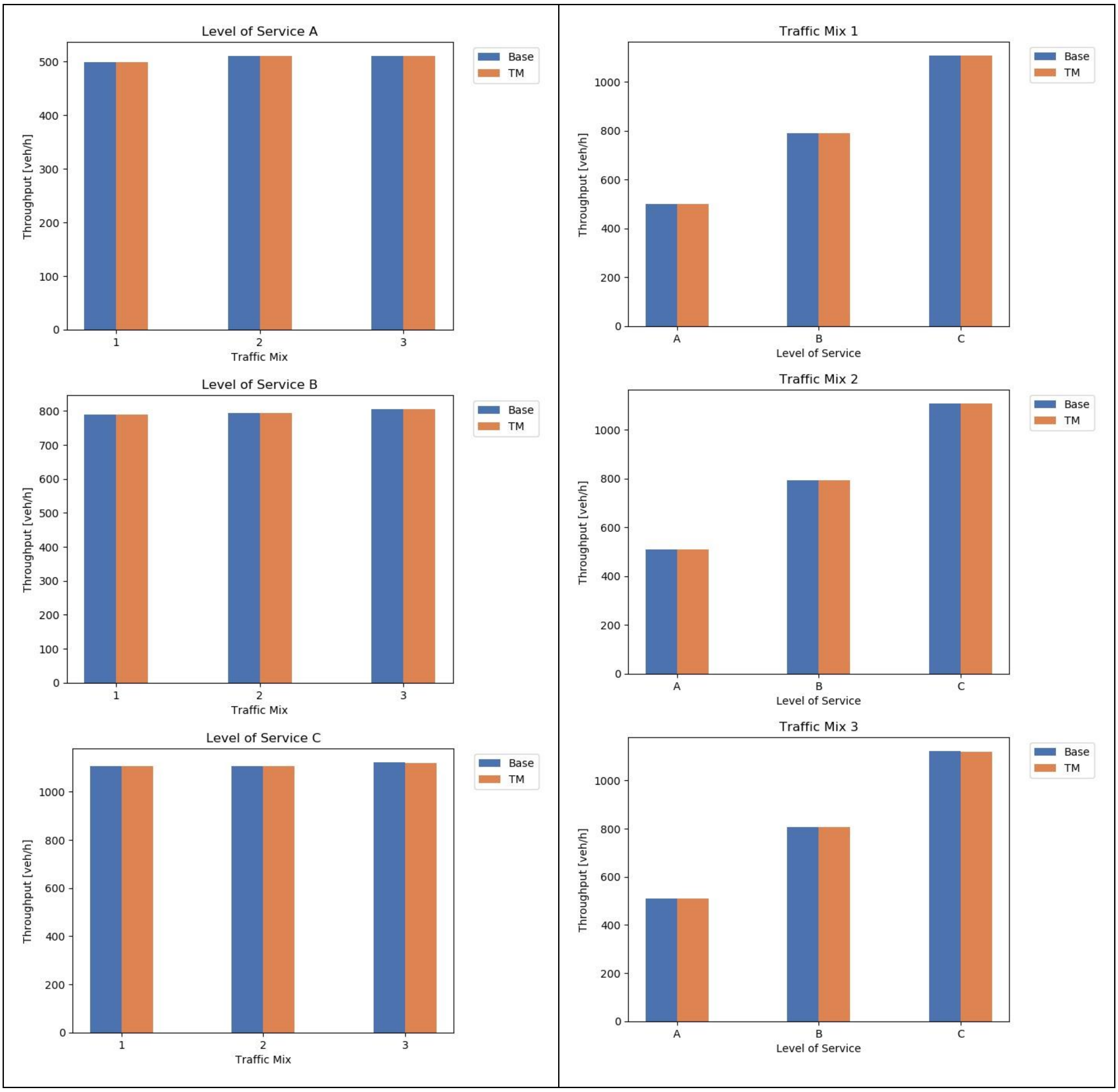


Figure 4: Throughput for use case 1.1 (varying the LOS and vehicle mix). Different bar colours correspond to the baseline and traffic management simulations.

Local Impacts

Similary to the negligible overall changes in speed and flow at different LOS and vehicle mixes, the local differences between the baseline and the traffic managed case are also small (see Figure 5 for example). The main difference is the change in speed right downstream of the location where the bus lane is available for all vehicles. The reason for this is that LVs start changing lanes towards the bus lane around this location. It is usually occupied by some of the C(A)Vs which receive the path information earlier. Due to the associated merging interactions, the speed at kilometre point 0.7 is slightly lower for the traffic managed case compared to the baseline. However, this local speed reduction does not cause any recognisable change in flow (as can be seen in the time-space diagrams of Figure 5. An explanation of these diagrams is provided in Section 5.2 of Deliverable D6.1).

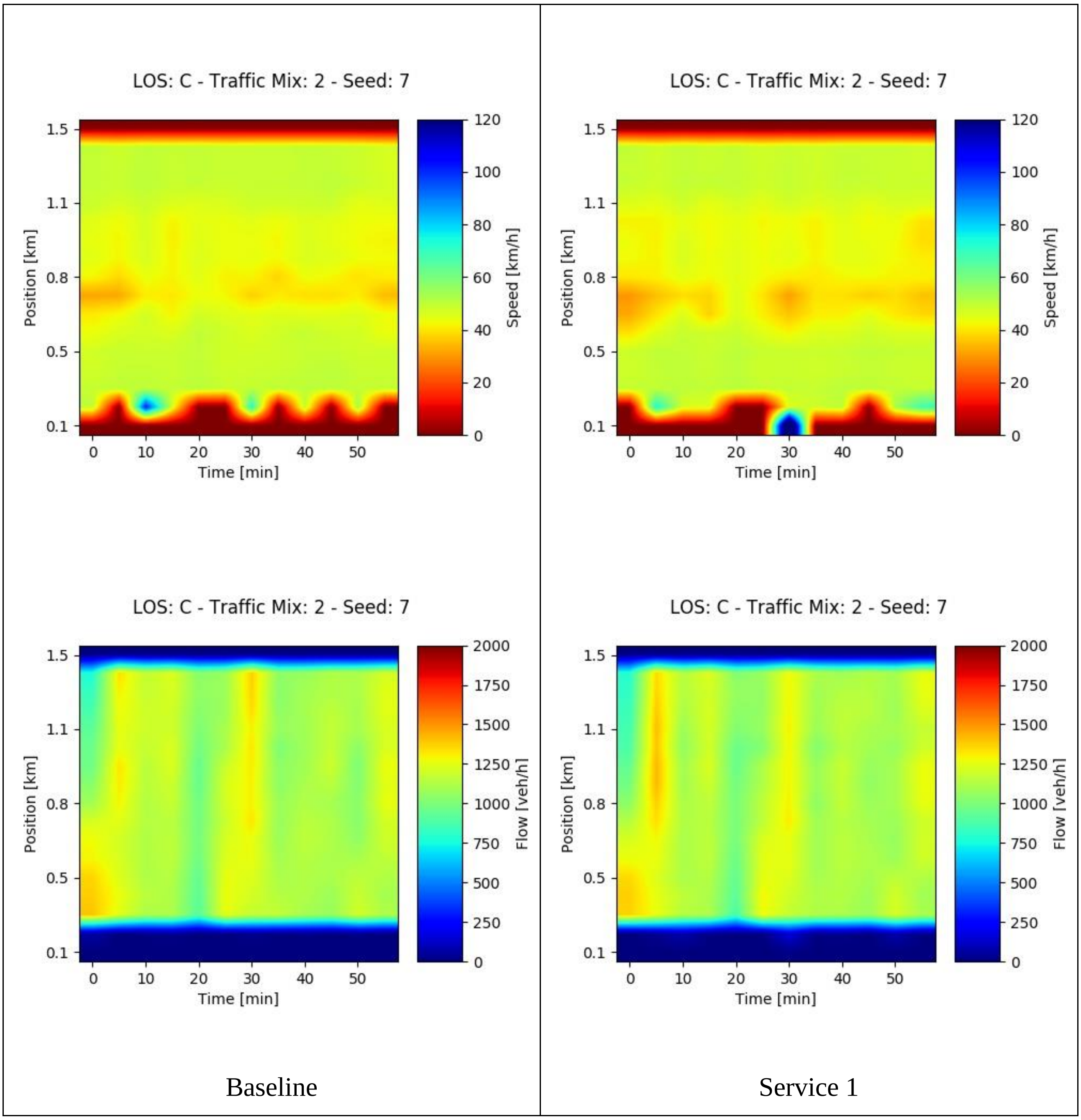
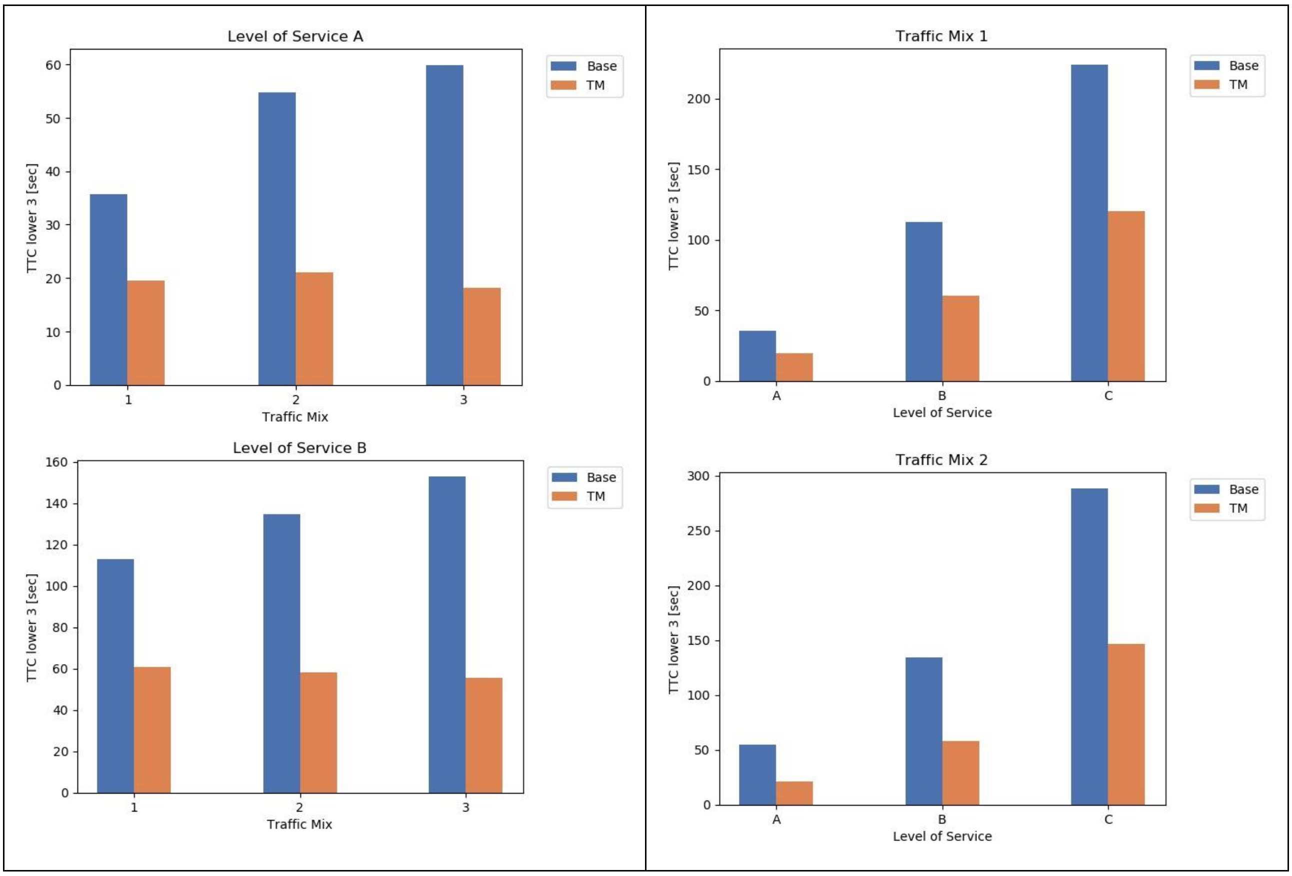


Figure 5: Example time-space diagrams for measured speeds and flows at LOS C with vehicle mix 2 for use case 1.1. The left group corresponds to the baseline simulations, the right group to those where Service 1 is applied.

3.1.1.3.2 Impacts on traffic safety

To analyse traffic safety we use the time-to-collision (TTC) KPI to measure the longitudinal margin from the current vehicle to its lead vehicles or objects. A more detailed explanation about TTC can be found in Section 3.7 of Deliverable D3.1. When the TTC of a vehicle in an interaction episode is less than three seconds, it is considered to be a critical event.

Figure 6 shows the number of critical events with a TTC lower than three seconds for the different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and traffic management service (note that the scaling of the number of critical TTCs is not equal for every chart). Across all scenarios, the number of critical events is significantly reduced with the adoption of Service 1 in comparison to the baseline case. The reduction rate ranges from 45% to 70%. Figure 6 also illustrates that with more C(A)Vs deployed, a higher reduction of the number of critical events can be achieved at all levels of service. The reduction rate is 70% and 64% at LOS A and LOS B/C, respectively. Even with a high LV portion (70%) in traffic the average number of critical events can be reduced to about 45% – 47% in use case 1.1. This result demonstrates that more upstream availability of the path information and the introduction of the open-gap function can effectively improve traffic safety in the traffic situation facing changes in traffic lane use and roadway reduction.



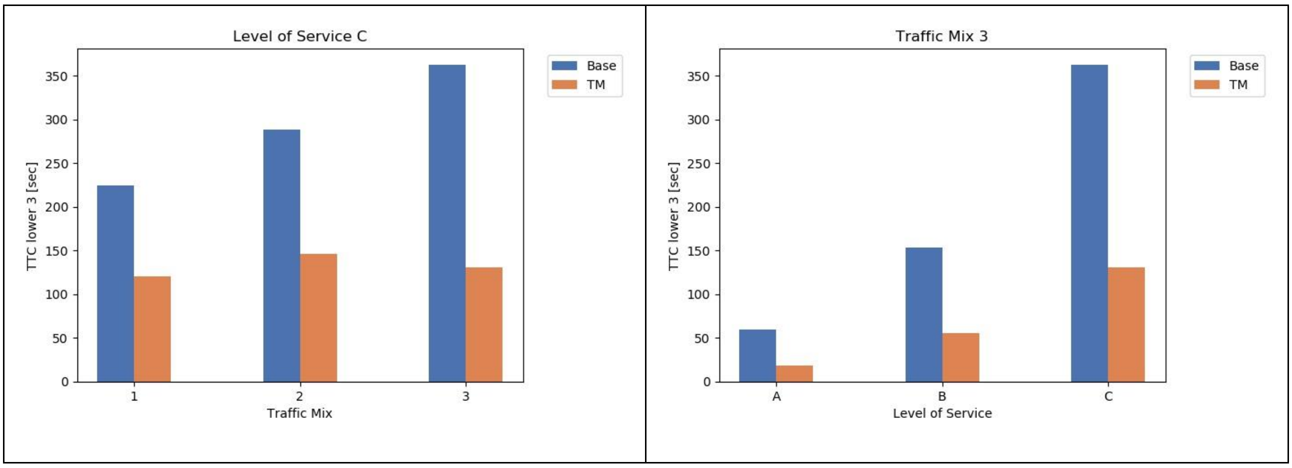
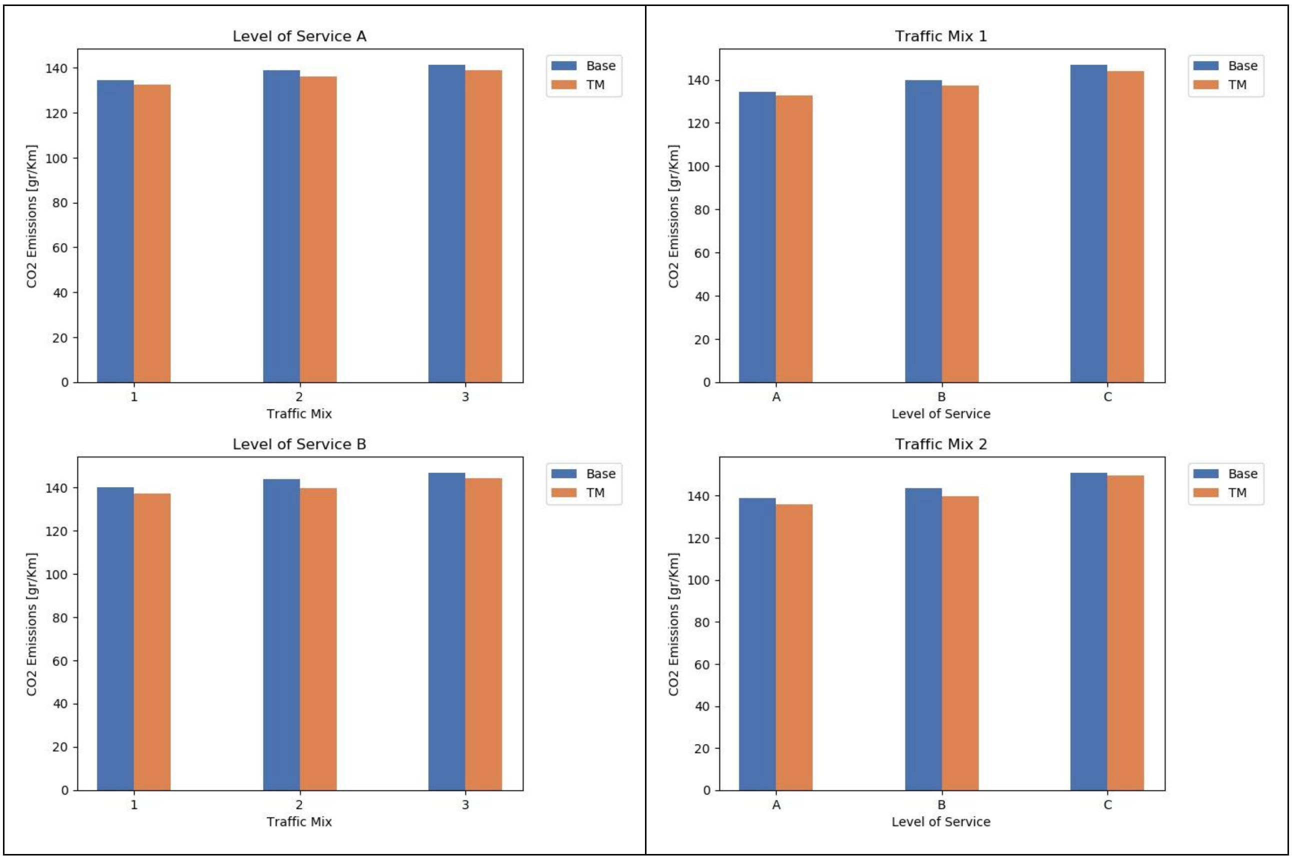


Figure 6: Average number of events with TTC below three seconds for use case 1.1 (varying the LOS and vehicle mix). Different bar colours correspond to the baseline and traffic management simulations.

3.1.1.3.3 Environmental impacts

For assessing the environmental impact of Service 1, we analyse the calculated emissions of CO_2. Figure 7 shows the average CO_2 emissions per travelled kilometre for the different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and the traffic management service (note that the scaling of average CO_2 emissions is not equal for every chart).

The results indicate that there is no significant difference in the overall CO_2 emission either with or without Service 1. The use of Service 1 results in a slight CO_2 reduction for LOS A and B and when C(A)Vs are not heavily deployed.



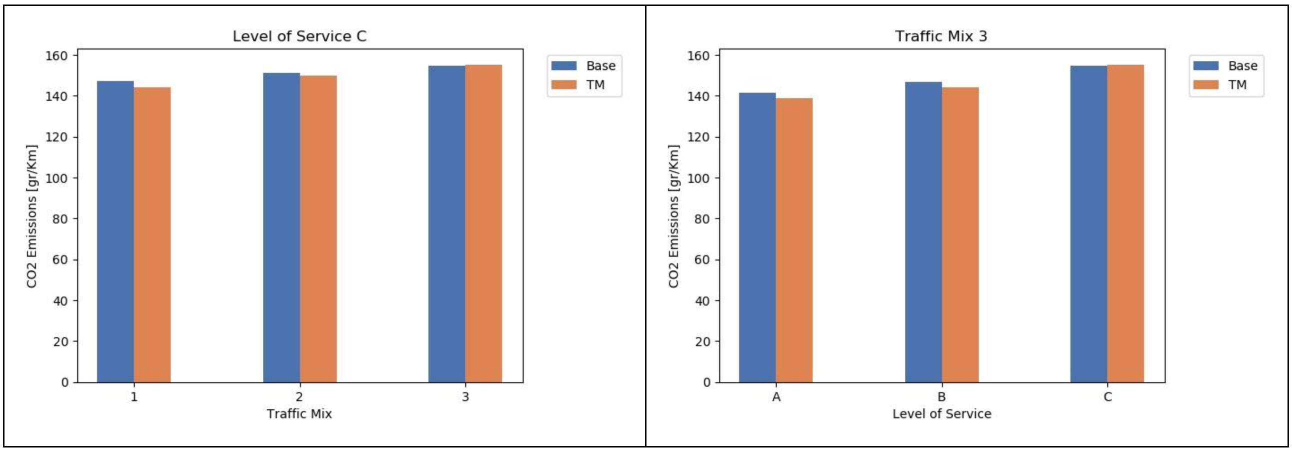


Figure 7: Average CO_2 emissions per kilometre travelled for use case 1.1 (varying the LOS and vehicle mixes). Different bar colours correspond to the baseline and traffic management simulations.

3.1.1.4 Discussion

According to the previous analysis of the results regarding the introduction of Service 1 in use case 1.1, there are no significant improvements on traffic efficiency and CO_2 emissions. Note however that none of these KPIs got worse for Service 1 in presence of a much lower ToC probability of 25% compared to 75% for the baseline. Especially for vehicle mixes 2 and 3 with higher vehicle automation rates this comes a bit as a surprise. We could have hypothesised that an increased usage of the bus lane would result in congestion for higher levels of service and induce a higher disruption by LVs merging into smaller gaps. In contrast, the open-gap functionality seems to compensate for that as intended so that we indeed do not observe an overall drop-off in traffic efficiency.

More importantly, we observe a major improvement in traffic safety with use of Service 1. The improvement has reached at least a 45% reduction in the number of critical events with TTC less than three seconds. When the deployment rate of C(A)Vs is higher than 80%, the reduction degree becomes more than 60%. This is also related to the reduced ToC probability and due to the deployment of the open-gap function which facilitates smoother and safer merge manoeuvres.

In conclusion, despite a reduced amount of takeover events, i.e. a larger share of C(A)Vs travelling with larger headways, and a general improvement of traffic safety, Service 1 does not induce any efficiency loss. The exact underlying mechanism should be studied in more detail and may be connected to the interactions of CAVs and LVs during a lane change. Indeed, due to the earlier merging of CAVs in the managed case we observe more often a situation where an LV merges into a lane, where a CAV is already present than vice versa. The quantification of the impact of the open-gap functionality under different parametrisations may be further examined to gain a better understanding.

3.1.2 Service 2 (use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice

3.1.2.1 Introduction

Having a direct impact on the capacity drop of a motorway, merging areas (such as the one for use case 2.1 shown in Figure 8) have always been an important research topic. Most of this research is based on queuing theory and statistics that do not combine various information sources obtainable from communication-capable vehicles, such as CVs and CAVs.

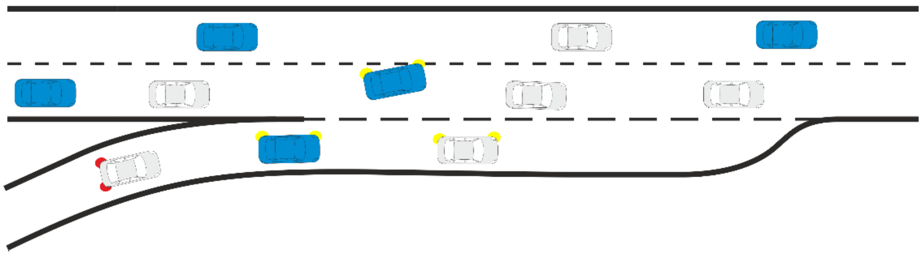


Figure 8: Schematic illustration of use case 2.1.

Therefore, contemporary ramp metering installations merely control the average capacity on a macroscopic level, rather than actively trying to prevent causing a capacity drop by addressing vehicles on a more individual level. The most commonly used strategy is ALINEA by Papageorgiou et al. (1991), which is based on the following equation:

$$r(k) = r(k-1) + K_{\mathrm{R}}\left[\hat{o} - o_{\mathrm{out}(k)}\right] \qquad (1)$$

In this equation r represents the on-ramp volume and k is the time step. K_R is a regulatory parameter which can be considered as a gain factor and o is the occupancy on the main road of the motorway. The equation basically implies that a certain occupancy is targeted, with a suggested time interval, which is usually between 20 to 60 seconds. This is a strategy on a macroscopic level that requires the set point to be significantly below the saturation point. This is because a traffic stream is never exactly homogeneous and a vehicle can arrive on the on-ramp during a particularly busy ten-second interval causing a shockwave that cannot dissolve by itself close to the saturation point.

Therefore, there is an opportunity to control the on-ramp closer to the saturation point when using a microscopic model of the traffic conditions. This was already considered in research that takes a connected vehicle environment into account, but only looked at a single vehicle from the on-ramp at a time. In other words, it did not aim to optimise merging delays by finding the optimal merging order. The research in use case 2.1 is motivated by the fact that it is not easy to guarantee safety for automated vehicles in these situations. Human drivers usually analyse a longer stretch of the main road to select a good place to merge. According to that, they decide to increase or decrease their speed as they approach the merging area. For the automated vehicle the sensors only observe what is happening on the main road when the lane of the on-ramp is already close to the main road. Therefore, it is very well possible that the small area that is monitored by the sensors does not contain a suitable gap to merge. Since this cannot be predicted by the vehicle, a ToC has to be issued before the actual merging area.

The area that can be taken into account for merging gap selection is illustrated in Figure 9. The AV will only observe a small area at a late moment, so there is also not a lot of time for performing speed adjustments. The human driver without infrastructure assistance can observe a larger area while being further away from the merge point. This means there is more time to adjust the speed to arrive at the selected gap when reaching the merging area. For a C(A)V, the infrastructure can already select a gap once the vehicle enters the on-ramp, long before there is visibility, allowing an even larger area to select a gap from. If this system is attached to a ramp metering installation, the system can simply wait for a gap to appear. Additionally, when the gap is large enough, multiple vehicles can even be released at once.

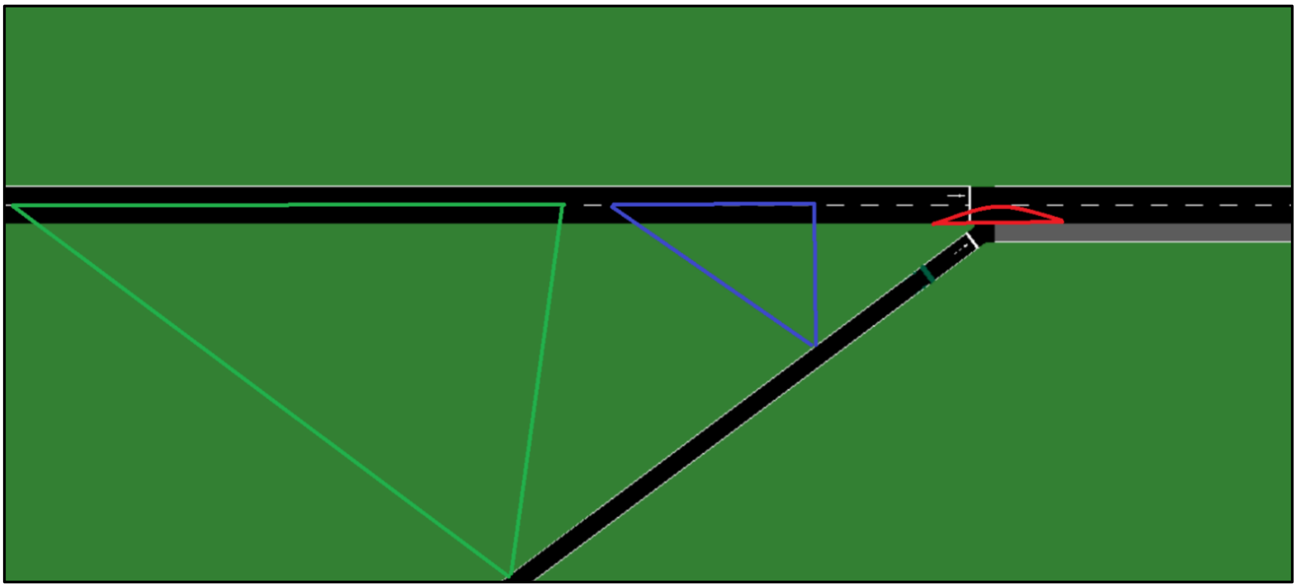


Figure 9: Schematic overview of the decision area for gap selection for AVs (red), LVs (blue), and infrastructure-assisted C(A)Vs (green).

Contemporary research focussing on assisting (automated) vehicles equipped with Cooperative Intelligent Transportation Systems (C-ITS) also shows that it will deliver a solution to the aforementioned conflict problems such as deteriorating traffic safety, speed breakdown, and congestion at merging bottlenecks, as described by Ntousakis et al. (2014). For example, Milanés et al. (2014) present the design, development, implementation, and testing of a CACC system conducted at the PATH program in cooperation with Nissan Motor Co. They demonstrate that intelligent vehicle cooperation based on reliable communication systems contributes not only to reducing traffic accidents but also to the improvement of traffic flow.

The first framework developed for lane changing is still used nowadays. It is the model of Gipps (1986). He poses three questions for a driver’s decision to change lanes, namely:

1. Is it possible to change lanes?
2. Is it necessary to change lanes?
3. Is it desirable to change lanes?

Merging is a special case of lane changing, as the answer to the second question is always ‘yes’ due to the fact that the lane the ego-vehicles are travelling in, ends or is blocked. Objectively, the merging vehicles behaviour boils down to the decision making based on a gap acceptance criterion. This implies that decisions are driven by the mergers’ maximisation of their own safety. This merging process can be described as below:

- Drivers chose safe gaps (i.e. distances between the putative leader and the putative follower) meaning that gaps above a certain threshold might be considered as acceptable.
- Drivers minimise the difference of their own speed and the ones of their putative follower and leader.

More recent research on lane changing behaviour can be found in the work of Daamen et al. (2010). The work by Choudhury (2007) presents a more sophisticated merging model for mandatory lane changes. This model introduces a unified decision framework for drivers with latent plans. However, it searches for gaps that are currently present close to the vehicle and does not plan for merges far in advance.

Service 2’s implementation of the ‘Prevent ToC/MRM by providing speed, headway and/or lane advice’ service will provide speed advice to vehicles upon entering an uncontrolled on-ramp. In this way, the benefit of the increased search space as indicated in Figure 9 is maximised. The main objectives are to reduce the need for ToC by finding a safe spot to merge for CAVs and to reduce the impact on main road traffic by preventing forced merges into small gaps.

3.1.2.2 Traffic management setup

3.1.2.2.1 Merging algorithm design

The cooperative merging system is an iterative, distributed intelligent control system that aims for safe and optimal vehicle manoeuvres of LVs, CVs, and (C)AVs. There are two main objectives of this research:

1. No two vehicles coming from the on-ramp and main road will collide (rear-end or lateral collisions) nor have problems executing their speed advice, due to them targeting the same gap.
2. Each cooperative merging sequence produces the lowest average merging cost, which is the estimated minimal average time to reach the so-called Merge Decision Point (MDP) for all traffic.

Note that the estimated time to reach this MDP is chosen as the optimisation target instead of distance to reach the MDP, because having two equidistant vehicles does not necessary mean that their trajectories are conflicting. The most straightforward approach to set the priorities of merging for all arriving vehicles is to follow the FIFO queue discipline (‘First In First Out’ or ‘First Come First Serve’). To answer the question who will be the first, the time to reach the MDP could be used to determine the Merging Sequence (MS) and the insertion gaps.

However, determining the MS according to the FIFO principle, may not give the most optimal solution for the overall traffic. A vehicle at the on-ramp may be merging at a moment that the density at the main road is high and consequently cause a disruption that turns into a shockwave traffic jam. Therefore, a certain minimum gap size is required, otherwise the cost of future vehicles increases sharply as they first have to pass a traffic jam before reaching the MDP. The calibration of the parameters that evaluate the gaps determine the ratio of the impact on main road traffic and on-ramp traffic.

Deliverable D4.1 already mentioned a hierarchy of measures that should be applied in case of certain traffic conditions. However, the work of implementing the service into simulation led to new insights. It is never safe to just let a CAV enter the on-ramp without any guidance. They may arrive at the same time as a dense platoon and this risk cannot be taken. Therefore, the baseline strategy of doing nothing would require all CAVs on the on-ramp to issue a ToC, except for those CAVs that happen to find a convenient gap between first merge point and the decision point (placed 65 meter into the acceleration lane, as can be seen in Figure 10). The core strategy is to provide guidance to vehicles on the on-ramp, as this has a minimal impact to the main road and thus should always be deployed. Coupling this to an upstream traffic light controller (TLC) or to a ramp metering system effectively increases the size of the search space as indicated in Figure 9. Since the guidance strategy is always based on models of the actual traffic situation, there is a possibility that the gap unexpectedly disappears. In such a case, a ToC and/or an MRM has to be issued. Therefore, this strategy should also always be switched on as a fail-safe. In theory a ramp metering system can wait infinitely long for a gap, but traffic management calibration should of course determine a certain minimum average volume that should enter the on-ramp (to limit queueing on the ramp itself with possible spillbacks), even if it implies these vehicle have to issue a ToC due to a high volume on the main road. Other strategies include speed and lane guidance on the main road. These latter two, as well as ramp metering, will be further investigated in the second iteration. An extra strategy that was developed was to disallow vehicles on the left lane to go back to the right lane in the modelled area (Figure 10).

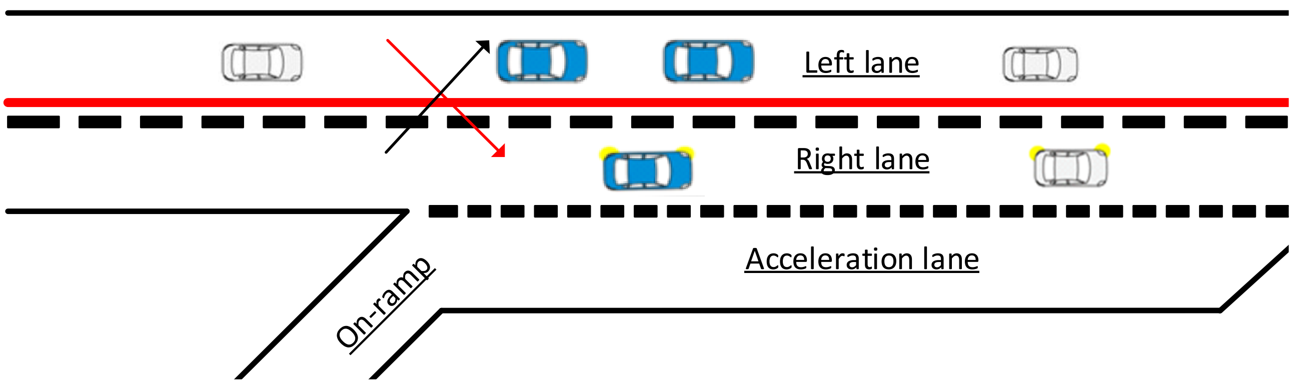


Figure 10: Schematics of the new lane advice strategy in current iteration.

In Figure 10, there are two putative lines (one black dash line and one red solid line) between the left and right lanes to demonstrate this new strategy. The black dash line means that the vehicles on the right lane are emulated as real traffic now. They can perform cooperative or tactical lane changes to the left lane but no advice is given. The red solid line means that the vehicles on the left lane are prevented from using the right lane when they are travelling in the cooperative zone (indicated in Figure 13). This is a very helpful strategy to prevent surprises in the model and to keep the density at the right lane lower, which is also discussed later on.

The core merging algorithm of the combined merging assistant and traffic management strategies is shown below in Figure 11. This state diagram is composed of four components: (i) the core merging algorithm, (ii) the Traffic Management Centre (TMC), (iii) the cooperative data, and (iv) the camera data. The latter three are individual blocks that combine and coordinate with the core merging block. Starting from the centre of merging algorithm, a mainline right lane vehicle M_{oj} and an on-ramp vehicle R_j enter the network, detected by the entry-loop detectors on mainline -1580 and on-ramp -980. To both of them, the algorithm asks the question what type of vehicle it is, and gets the information about the vehicle speed, position, and ego-lane leader-gap. The algorithm also asks them to keep the current lane and speed if it is a CAV (or as much as possible for CVs and CAVs). The algorithm projects the mainline vehicle M_{oj} to mainline -980 position, to have equivalent distance with on-ramp vehicle R_j. With the retrieved information on the vehicle speed, position, and leader-gaps, the algorithm tries to search for possible merge gaps. If merge pairs found, the algorithm gives a speed advice accordingly to on-ramp vehicle R_j. If not, the simulation time is increased by one second to search for possible gaps until the time length to reach the possible gap is greater than the time to reach the last merging point. If no gaps are found at this point, the algorithm asks if there is any CAV on the main road's right lane for a cooperative merging possibility. If not, the algorithm issues a ToC to on-ramp vehicle R_j and if the ToC is not successful, it goes into MRM mode, as the ToC and MRM method described in Deliverable D3.1.

The TMC works on a higher hierarchical level to monitor the network traffic situation. The merge success rate and all vehicle information feedback, which are gathered through entry-loop detectors, cooperative data of CVs and CAVs, as well as camera data, are sent back to the TMC for traffic demand control. The gap level on the main road and on the on-ramp are closely controlled by the TMC and it starts vehicle input control, such as ramp metering, upstream adaptive TLC to manage the traffic demand.

The last two components are important for the algorithm and the TMC as well. Cooperative data from CVs and CAVs can adjust the leader-gap in real-time for an accurate implementation of the algorithm. Besides serving the same function, camera data can also report on the information of LVs, which would otherwise only be estimated based on entry-loop detectors.

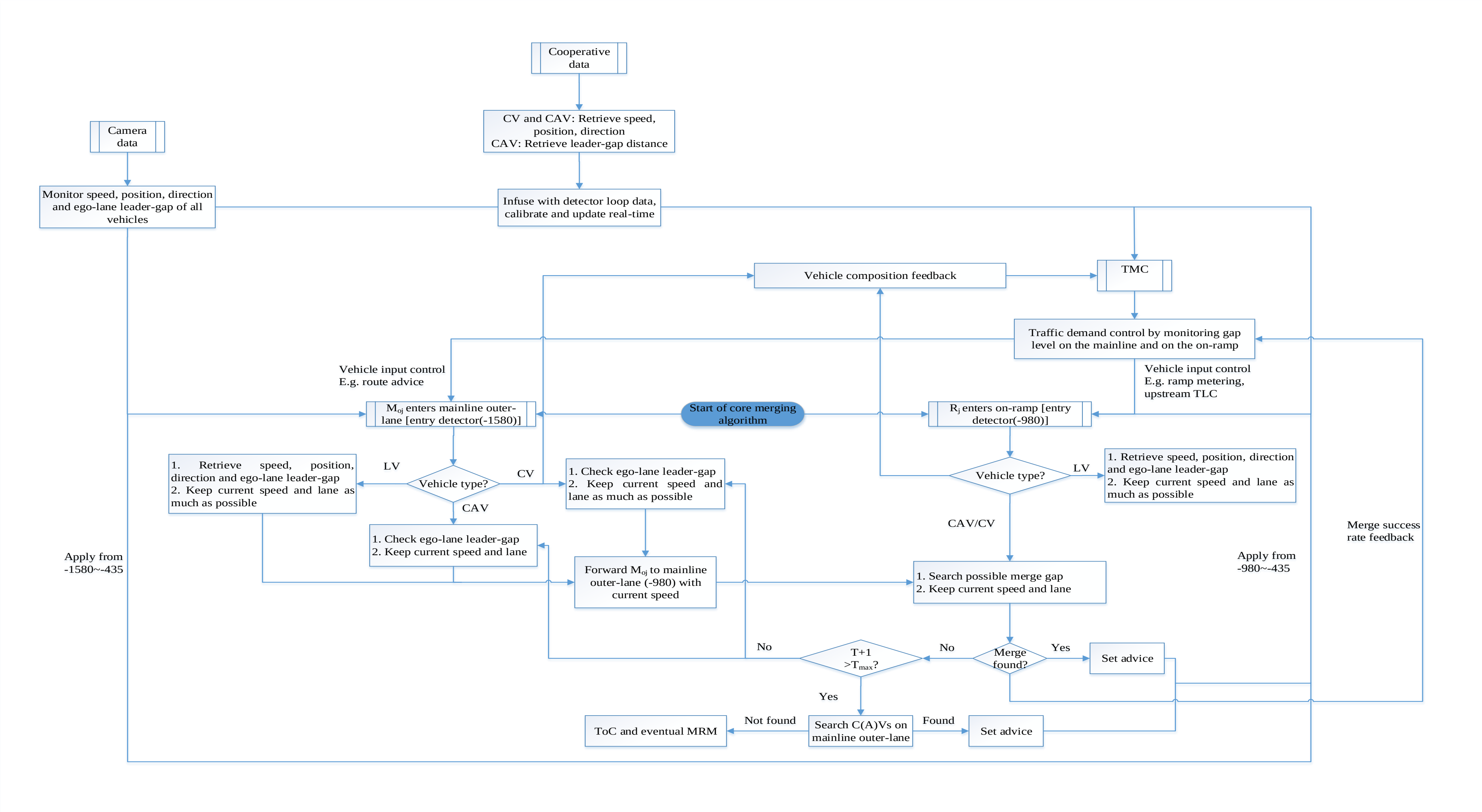


Figure 11: The core merging algorithm flow chart for Service 2.

The on-ramp guidance depends on the traffic model behind it. The quality of the information of this model is vital to the performance of the guidance strategy. It is configured by several parameters as shown in the following Table 2.

Table 2: System parameters of merging assistant.

Parameter	Default value	Description
detectorIDs	Take from det.add.xml	These detectorIDs are required for the model to feed the entry detection for the main road lanes and the on-ramp lane with data.
Main road detector distance	-1580 m	The distance from a detection to the end of the merging lane. Note that the detection takes place at the falling edge of the detector pulse, which means that the vehicle just left the detector. In practice the detection is 5 m ahead of the detector.
On-ramp detector distance	-980 m	Similar to the main road detector distance, but then for the on-ramp.
Cooperative detection	ON	Whether cooperative data is fused with the detector data. This improves the model significantly.
CAV leader detection	ON	Whether data from the CPM is used to determine the distance between the CAV and the vehicle ahead of it. This can increase the accuracy significantly, especially in the presence of many LVs.
Camera detection distance	-600 m	The starting point of tracking sensor data that gives an update about lane, speed, and position of each vehicle within range.

The system has several configuration options, which are explained in Table 3:

Table 3: Merging configuration parameters.

Parameter	Default value	Description
Minimum gap	2.8s	The minimum gap between a putative leader and follower required for selecting it as a guidance target.
Maximum speed	27.78 m/s	Maximum advised speed, effectively defines the start of the search space for a gap. Should be equal to or below the speed limit.
Minimum speed	16.67 m/s	Minimum advised speed, effectively defines the end of the search space for a gap. Should be a safe speed to keep

		when human drivers are present.
Last merge distance	-100 m	This is the distance required for CAVs to execute an MRM. Not directly used in the algorithm, but useful to monitor in the GUI.
Merge Decision Point (MDP)	-435 m	The target point for which the advice is valid. The closer to the end of the lane, the larger the search space due to the increased distance over which the speed can be controlled. Should contain a margin for vehicles to execute a ToC and MRM if the driver does not take over in time. Once a vehicle reaches this point, the service makes a final decision whether the guidance was effective. If this is not the case and there is no gap sufficient for merging, a ToC is issued.
First merge distance	-500 m	The point where the merging area starts. This is not directly used in the algorithm but is useful to monitor in the GUI.
ToC type	vehCVToCRPS	Vehicle type in SUMO to which a vehicle should change when a ToC is issued.
Left lane hold	ON	This prevents vehicles in the merging area from switching back to the right lane.

Note that the distances are all relative to the end of the merging lane. So -100 m means it is 100 m before the end of the merging lane. Coming back to the ramp metering strategy, it effectively reduces the minimum speed to 0 m/s.

When an update to the model results in the conclusion that a ToC will be needed in the future, it is issued immediately and the service does not wait until the MDP. This increases safety as it increases the time the driver has available to take over control and start selecting a gap manually.

3.1.2.2.2 Traffic management zoning

Lane change behaviours can be generally classified as being mandatory or discretionary. Considering the lane change intention, the LC2013 Model of SUMO categorises lane changes into strategic, cooperative, and tactical, where strategic lane changes correspond closely to mandatory lane changes because they both depict situations of lane changes such as route keeping and dead-end avoidance.

The merging zone schematic of use case 2.1 during the baseline simulation was proposed in Deliverable D4.1, as reproduced here in Figure 12. It depicts the boundaries of transition areas on the motorway on-ramp. In the baseline simulation, we assume that no infrastructure-assisted traffic management control measures are enabled. Therefore, the CAVs (blue) and CVs (white) are requested to perform ToCs (consequently MRM) at 250 m upstream to the merging zone. The compliance rate of ToCs is 75% on both the main road and on-ramp. The LVs (light-coloured) in the schematic consist of original LVs and ‘after-downward-ToC’ LVs (from CVs and CAVs). At 50m downstream to the end of merging zone, all ‘after-downward-ToC’ CVs and CAVs instantaneously change back to their original properties.

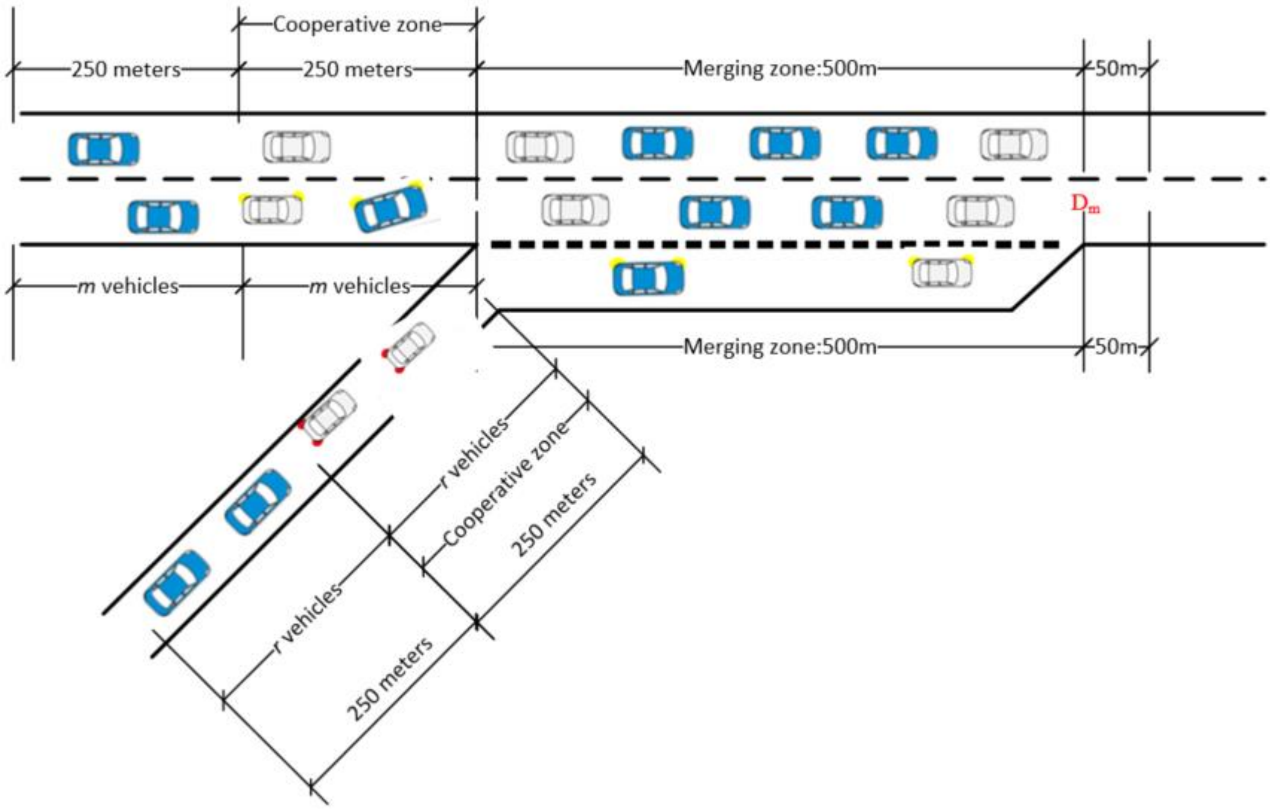


Figure 12: Merging zone schematic (baseline) of the network for use case 2.1.

However, this scenario was not suitable for implementation of the merging assistant service. With only 250 m of road before the merging area, there was little opportunity to direct vehicles towards a suitable gap. Additionally, the model on the main road should start further in advance to have information about the approaching traffic if the guided vehicle would slow down. Therefore, any valid scenario should have detection placed according to the following condition:

$$\frac{d_{\mathrm{M}} - \mathrm{MDP}}{v_{\max}} \geq \frac{d_{\mathrm{r}} - \mathrm{MDP}}{v_{\min}} \qquad (1)$$

With d_{M} and d_{r} the distance of the main road and on-ramp detectors and $v_{\max}$ and $v_{\min}$ the maximum and minimum speed, respectively. This condition implies the minimum time a vehicle on the main road can take to reach the end of the merging area should be larger than or equal to the maximum time a vehicle at the on-ramp can take. With the default configuration used in this research, the main road traffic takes at least 41.2 s, while the on-ramp traffic takes at most 32.7 s. The minimum time to reach the merging area from the on-ramp is 19.6 s, creating a search space 13.1 s. With this condition, the main road entry detectors are placed on coordinates (-1580, 0) and the on-ramp entry detector is placed on on-ramp coordinates (-980, 0).

As the traffic complexities of giving speed advice under the safety constraints of (C)AVs and CVs arising on the network for Service 2, Figure 13 shows the new zoning indication according to the service's requirements. The SUMO simulation network is directly used in this figure and the x-axis is set up on the main road while the y-axis is perpendicular to the main road. The GUI of the merging assistant system is shown in the upper part of Figure 13, which gives real-time, intuitive indications of the traffic situation and vehicle behaviours on the on-ramp and main road. Thus, a clear view can be given at run-time, as well as for presenting, spotting, and debugging the merging assistant system.

There are several important points and sub-areas in Figure 13, which are explained below with the rationale behind them:

Points

- Main road entry detectors (-1580, 0)
- On-ramp entry detectors (-980, 0)
- First Merge Point (FMP) (-500, 0)
- Merge Decision Point (MDP) (-435, 0)
- Last Merge Point (LMP) (-100, 0)
- Lane Drop Point (LDP) (0, 0): this is also the camera set-up point; Camera detection distance is (-600~0, 0)
- Control revoke point (50, 0)

Sub-areas

- Traffic Management (TM) influenced zone: from the beginning of the network to the control revoke point
- Mainline cooperative zone (-1580~ -100, 0)
- On-ramp cooperative zone (-980~ -500, 0)
- Merging zone (-1580~ -100, 0)
- Transition Area (TA)+ Minimum-Risk Manoeuvre Zone (MRM-Z) (-435~ -100, 0)

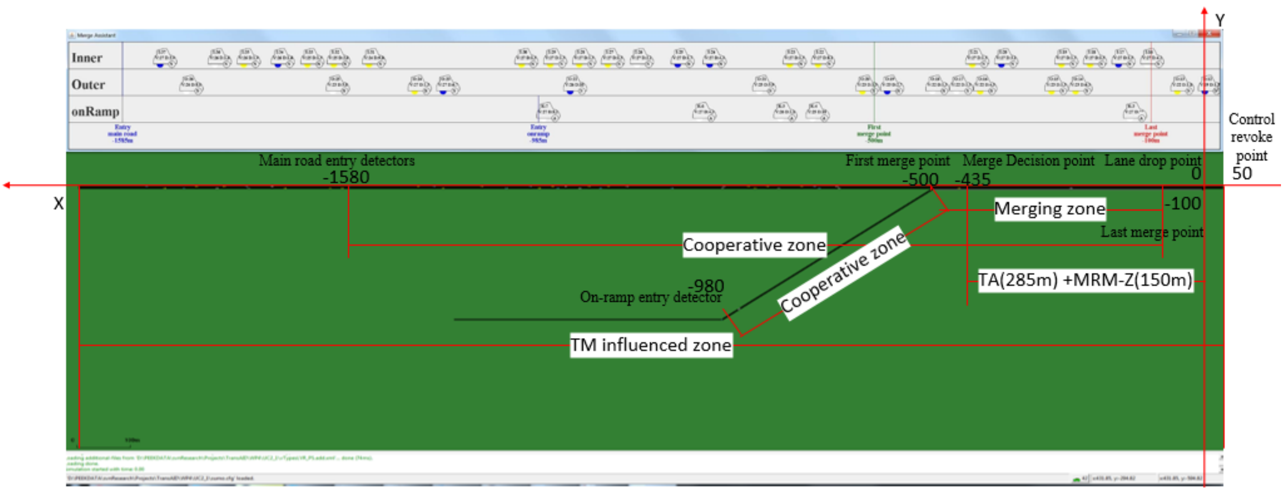


Figure 13: Zoning indication of the SUMO network for use case 2.1.

Calculation of sub-areas

At the Merge Decision Point, CAVs should know whether it is possible to have a merge opportunity on the merging zone horizon or not. A TA+ MRM-Z is obligatory to ensure safety, which starts from the Merge Decision Point to the Last Merge Point (see also Figure 13).

For the TA distance, the calculation is based on the vehicle speed and the available lead time (timeUntilMRM in the simulation script of Deliverable D3.1) of CAVs. A rough calculation of TA distance equals the available lead time (10 s) × 27.28 (100 km/h) = 272.8 m. An approximation of 285 m is chosen.

If the take-over time exceeds the available lead time, then the ToC fails and the CAV enters the MRM-Z. For safety reasons, it is crucial that a CAV can have a full stop on a safe bay (right-most lane/shoulder lane) before the Lane Drop Point. The braking distance during MRM is calculated based on the following equation:

$$d = \frac{u^2}{2a_{\mathrm{MRM}}} \tag{2}$$

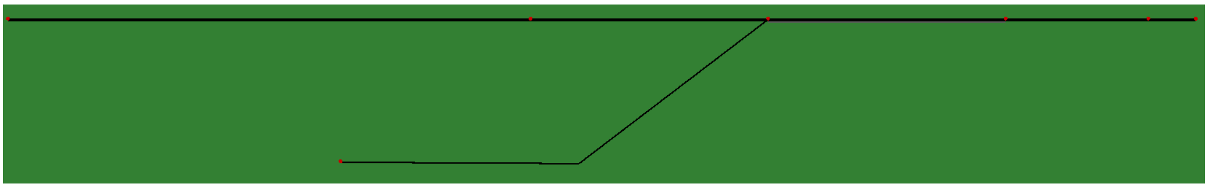
where u is the vehicle initial speed, and a_{MRM} is the deceleration rate during MRM. For CAVs travelling with the speed limit $v_{\mathrm{lim}} = 36.11\ \mathrm{m/s}$, and capable of braking during MRM with deceleration rate equal to $a_{\mathrm{MRM}} = 3.0\ \mathrm{m/s^2}$, the braking distance is estimated equal to $d = 220$ m. The initial vehicle speed is $27.78\ \mathrm{m/s}$, and a_{MRM} is the deceleration rate during MRM, which equals to $3.0\ \mathrm{m/s^2}$. Therefore, the braking distance $d = 128$ m. A reservation of 150 m for the MRM-Z is made as a margin to prevent a full stop at an unsafe place due to the road's geometry.

3.1.2.2.3 Baseline scenario adaptation

As already explained, the network of Service 2 is not applicable anymore to provide speed advice. Table 4 shows the adapted network configuration details with changes marked in yellow, considering the design constraints in this section. The junctions and edges are kept the same, while two edges were extended to have stabilised speeds due to vehicle injection perturbation of emergency braking in the SUMO simulator. The on-ramp speed is increased from 80 km/h to 100 km/h to have a more homogeneous traffic flow.

Table 4: Adapted Network configuration details for use case 2.1. Changes in yellow.

UC2_1	Settings	Notes
Road section length	• Highway: 1.5 km→2.5 km • On-ramp: 0.5 km→ 1.0 km • Acceleration lane: 0.5 km	
Road priority	3	
Allowed road speed	• Highway: 27.78 m/s • On-ramp: 22.22 m/s→ 27.78 m/s	• Highway: 100 km/h • On-ramp: 100 km/h
Number of nodes	7	• jun1 - jun7 priority nodes
Number of edges	6	
Number of O-D relations (routes)	2	• from jun1 to jun7 • from jun3 to jun7
Number of lanes	1-2-3-2	• 1 lane on-ramp • 2 normal lanes on highway • 3 lanes at merging zone (from jun4 to jun5, including acceleration lane)

		• 2 lanes downstream of the merging zone. Thus, a lane drop from 3 to 2 lanes at the end of merging zone.
Filenames	• network: UC2_1.net.xml	
Merging area length	0.5 km	
Network layout 		
Network layout 		
Road segments jun1→ jun2: Insertion and speed stabilisation area (100 m→1100 m, 2 lanes) jun2→ jun4: mainline motorway (500 m, 2 lanes) jun3→ jun4: on-ramp (500 m→1000 m, 1 lane) jun4→ jun5: mainline motorway with acceleration lane (500 m, 3 lanes) jun5→ jun6: mainline motorway (300 m, 2 lanes) jun6→ jun7: exit (100 m, 2 lanes)		

3.1.2.2.4 Simulation scenarios set-up

In this deliverable, we keep as much as possible the demand and vehicle mix from Deliverable D3.1 for consistency. For the vehicle mix, the composition of the three classes of vehicles stays unchanged. The on-ramp vehicles are 100% CAV in all scenarios, as LV are not interesting for the service and were thus not used on the on-ramp.

All simulation settings for Service 2 are recapitulated in the tables in the Appendix in Section 5. The basic network did not change. Therefore, the two-lane motorway capacity is the basic capacity for the simulation network in Scenario 2.1. The vehicle injection rates on the on-ramp entry link and the upstream freeway entry link together should not exceed downstream two-lane motorway service flow rates. The two entry links – upstream motorway and on-ramp – are then injected with approximately 5/6 and 1/6 of these respective rates. Higher than 1/6 for the on-ramp demand should be considered a worst case. Additionally, there is a model inaccuracy, where vehicles that were given a ToC advice after a speed advice performed very poorly with merging when compared to vehicles that did not receive a speed advice while being in identical situations. This created unrealistic traffic jams that should first dissolve before a new vehicle enters the merging area, otherwise a model inaccuracy is affecting multiple consecutive situations.

For the simulation scenarios set-up, there are three dimensions in total. The vehicle mix dimension and the traffic demand dimension are the same as explained above. The parametrisation scheme of ACC, SL2015, ToC/MRM response time, post ToC driver performance and MRM likelihood are fixed to Moderate Safety and Efficiency (MSE), based on the simulation results of Deliverable D3.1.

A new dimension is introduced for use case 2.1 during development of the merging system: the traffic management intensity. It has baseline, ToCOnly and normal (speed advice); see Table 5 for a further description of each intensity.

Table 5: Scenarios according to traffic management intensity.

Traffic management intensity	Description
baseline	The merging assistant system is on but only observe the traffic situation. All CAVs will perform ToC/MRM if there are no imminent merging possibility from first merging point to decision point.
ToCOnly	The merging assistant system is on and besides observing the traffic situation it issues ToC to CAVs when no merging possibility is found before the decision point. This means the ToC/MRM could be issued early on the on-ramp due to the prediction of merging assistant system.
normal	The merging assistant system is fully on with all configurable functionalities and it collects traffic data, and then calculates the speed advice for on-ramp CAVs. If merge not found, it issues ToC/MRM to on-ramp vehicles.

To summarise, there are in total 27 scenarios based on different traffic management intensities, vehicle mixes and traffic demands. Simulations of each scenario are carried out accordingly with 10 runs, one hour per run.

3.1.2.3 Results

Conclusions from Deliverable D3.1 showed some intriguing correlations among merging, congestion, and safety-critical events:

1) Congestion at lane drops is highly correlated with safety-critical events.
2) Traffic safety is further undermined as the share of CAVs/CVs in the vehicle mix increases.

Point (1) is observable in the baseline simulation. At the lane drop location (end of on-ramp lane, zero coordinate on x-axis), the average speed decreases and congestion first appears at the lane drop, merging zone, and later on at the upstream main road as the traffic demand increases. From the baseline simulation results, the average speed reduction from LOS A to LOS B is more dramatic in the presence of a larger number of CAVs/CVs, because they decrease the capacity and consequently the region of free-flow. Upon the high correlation with safety-critical events, this is because CAVs/CVs were simulated more conservative in terms of their lane change behaviour in comparison to LVs. Therefore, they cannot merge early enough to the desired lane, which in return leads to sudden braking in front of the dead-end lane and consequently to rear-end conflicts due to car-following.

It can be seen from the previous results in Deliverable D3.1 that TransAID measures are needed to prevent, postpone, or distribute active congestions such as merging from on-ramp to motorway with a lane drop at the end of the merging zone. The cooperative merging system is designed to advise LVs, CVs and (C)AVs with speeds and positions to perform cooperative merging, in order to enable smooth coexistence of LVs, CVs, and (C)AVs in TAs.

3.1.2.3.1 Impacts on ToC rate and vehicle stops

As explained before, there are in total 27 scenarios due to three dimensions: traffic management strategies (baseline, ToCOnly and normal), vehicle mixes (1, 2 and 3), and traffic demands (LOS A, B, and C). The full simulation results for 10 runs of the baseline, under vehicle mix 2 and LOS A are shown in Table 6.

Table 6: Baseline simulation results.

Seed/description	on-ramp veh	ToC issued	ToC%	Stops(meanHaltPerVehicle)
1	201	101	50.24875622	0.11
2	213	116	54.4600939	0.13
3	206	117	56.7961165	0.17
4	198	97	48.98989899	0.12
5	199	112	56.28140704	0.15
6	193	112	58.03108808	0.12
7	225	119	52.88888889	0.15
8	177	90	50.84745763	0.12
9	227	119	52.42290749	0.11
10	194	101	52.06185567	0.17
Average	203.3	108.4	53.32021643	0.135
St. dev.	14.38784209	9.8	2.849804874	0.022022716
C_ToC%_Stops				0.38314697
C_#veh_ToC%	0.023669808			

The full simulation results for 10 runs of the ToCOnly, under vehicle mix 2 and LOS A are shown in Table 7.

Table 7: ToCOnly simulation results.

Seed/description	on-ramp veh	ToC issued	ToC%	Stops(meanHaltPerVehicle)
1	201	53	26.3681592	0.06
2	213	67	31.45539906	0.13
3	206	61	29.61165049	0.1
4	198	53	26.76767677	0.08
5	199	58	29.14572864	0.1
6	193	55	28.49740933	0.04
7	225	51	22.66666667	0.08
8	177	46	25.98870056	0.11
9	227	65	28.63436123	0.06
10	194	54	27.83505155	0.06
Average	203.3	56.3	27.69306444	0.082
St. dev.	14.38784209	6.148983656	2.286495658	0.026381812
C_ToC%_Stops				0.293407763
C_#veh_ToC%	-0.024817364			

When all features of the merging assistant service were used, the following results of normal (speed advice) scenario were retrieved, see Table 8:

Table 8: Normal simulation results (speed advice with MergingAssistant switched on).

Seed/description	on-ramp veh	ToC issued	ToC%	Stops(meanHaltPerVehicle)
1	201	17	8.457711443	0.04
2	213	12	5.633802817	0.01
3	206	12	5.825242718	0.02
4	198	5	2.525252525	0.01
5	199	15	7.537688442	0.03
6	193	12	6.21761658	0.02
7	225	9	4	0.01
8	177	9	5.084745763	0.02
9	227	11	4.845814978	0
10	194	8	4.12371134	0.01
Average	203.3	11	5.410723069	0.017
St. dev.	14.38784209	3.28633534 5	1.645495841	0.011
C_ToC%_Stops				0.815128199
C_#veh_ToC%	-0.123959411			
C_ToC%_Stops_all				0.873393885
C_#veh_ToC%s_all	-0.011523296			

As indicated before, without a model to determine whether a ToC is necessary, all vehicles should do a ToC and this would be the baseline. From the simulation, we observe that none of the simulations had any automated vehicles stopping or causing braking behind them due to cutting into a gap. The cooperative vehicles under manual control would still stop at the end of the on-ramp if no gap could be found easily. This also directly explains the large reduction of stops with the reduction of ToCs when the system is switched on. When looking within the values of

Table 7 and Table 8, there is a correlation coefficient of 0.29 between ToC percentage and number of stops for the ToCOnly strategy and 0.82 for the full merging assistant. On the other hand, when all values of both scenarios are taken into account at once, the correlation coefficient increases to 0.87, which is a clear indication that the preventing a ToC has a very strong effect on preventing a stop.

Another interesting correlation coefficient to investigate is between the number of vehicles that entered the on-ramp and the ToC percentage. This is -0.02 for the ToC only strategy and -0.12 for the full merging guidance. Overall the correlation coefficient is -0.01. Therefore, it can be concluded that the volume variance between runs with different random seeds did not have a significant impact on the performance.

The ToC percentage and its standard deviation of all scenarios are shown in Figure 14 and Figure 15. In Figure 14, we see increasing trend of ToC percentage with higher CAV/CV penetration and with higher traffic demand, for baseline, ToCOnly and normal scenarios. Another obvious observation is the decrease on ToC percentage when the merging assistant system is on (ToCOnly) or fully on (normal).

The standard deviation graph shows more scattered results, which means the merging assistant is having effects on the vehicles' merging behaviour but also affected by the vehicle platoons' randomness. This will be discussed in the conclusion section.

From the vehicle stops data in these three tables (retrieved via E3 detector set: entryExitDetectors are placed right before the three-lane stretch and right after the lane drop point), the average vehicle stops decreases from 0.135 (baseline) to 0.082 (ToCOnly), and then to 0.017 (speed advice).

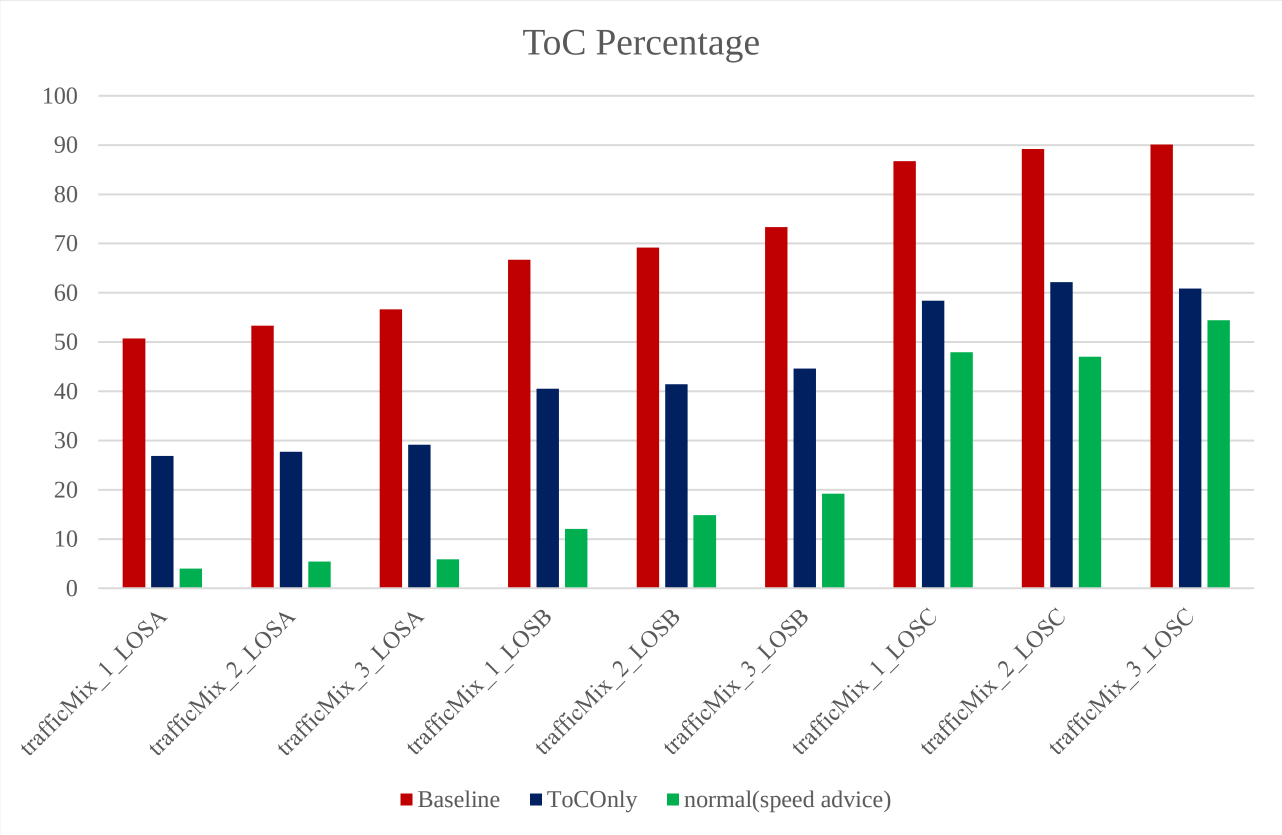


Figure 14: ToC% of baseline, ToCOnly and normal, under vehicle mix 1, 2, and 3, and LOS A, B, and C.

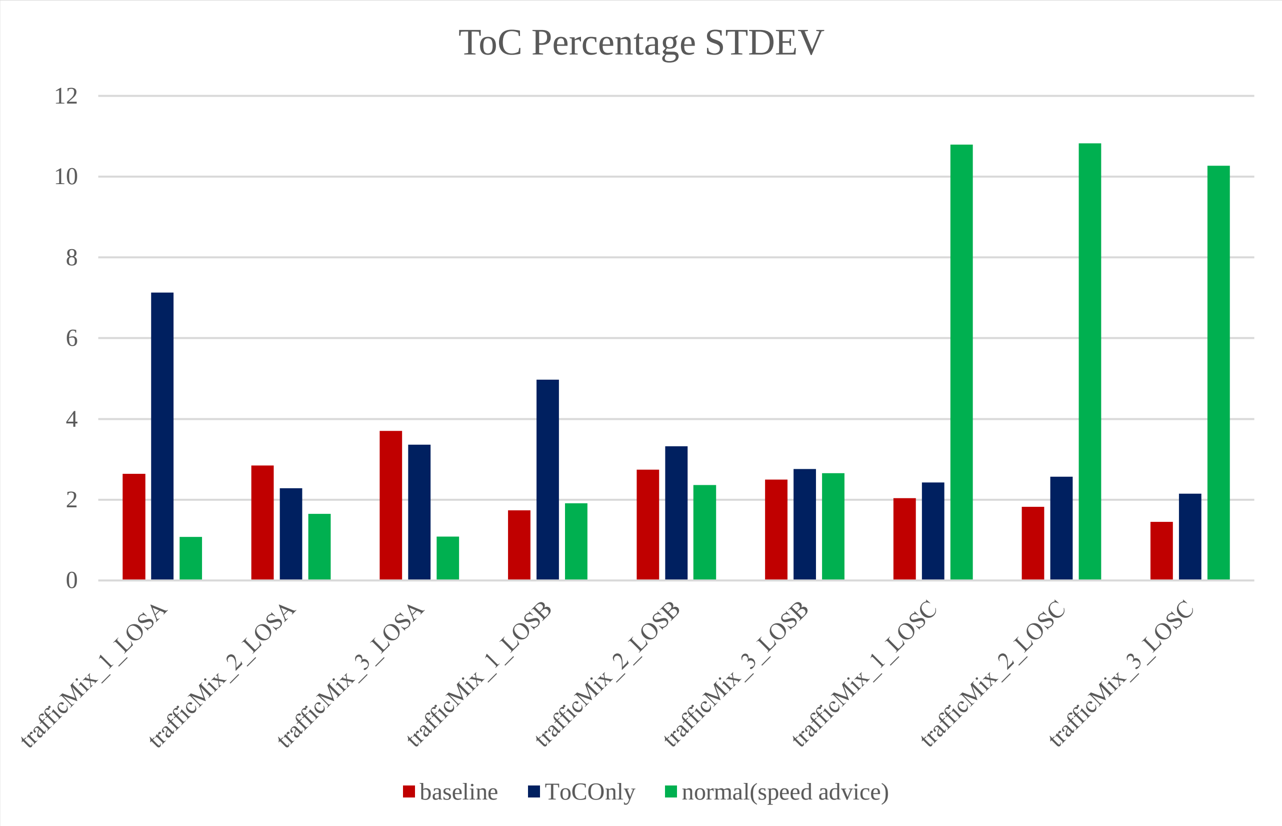


Figure 15: ToC% Standard Deviation of baseline, ToCOnly and normal, under vehicle mixes 1, 2, and 3, and LOS A, B, and C.

3.1.2.3.2 Impacts on traffic efficiency

Network-wide impacts

Figure 16 shows the average network speed of baseline (blue bar), ToCOnly (orange bar), and normal (green bar) for three LOS A, B, and C, and for three vehicle mixes 1, 2, and 3. It provides a comparison among traffic management intensity.

From the bar charts, the average network speeds of baseline, ToCOnly, and normal decrease as the LOS and vehicle mix level increase. The decrease is especially pronounced for higher vehicle mixes (higher C(A)V penetration). This phenomenon corresponds with results mentioned in Deliverable D3.1 because this deliverable adopts the same ToC behaviours as before for use case 2.1.

A slight average network speed increase can be observed for the normal (with speed advice) scenario, especially for a high demand (LOS C) and a high C(A)V penetration. This slight network speed increase could have been caused by reduced speed advice for the on-ramp vehicles. This phenomenon could change during the 2nd iteration where merge gaps will be actively created.

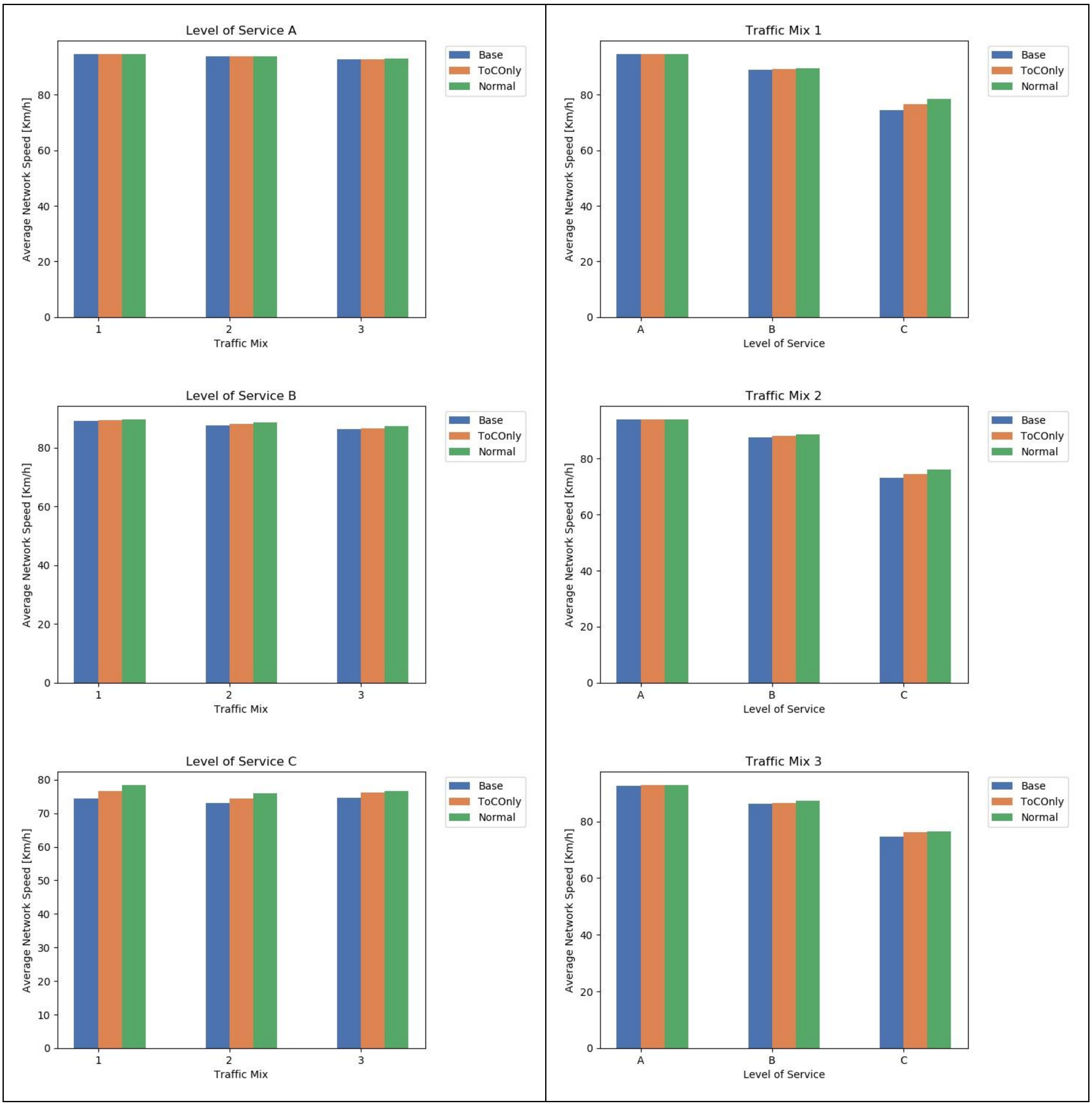


Figure 16: Average network speed for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

Figure 17 shows the throughput of baseline, ToCOnly, and normal for three LOS A, B, and C, and for three vehicle mixes 1, 2, and 3. For the most part, there is no obvious change across baseline, ToCOnly, and normal scenarios because the traffic demands are relatively low.

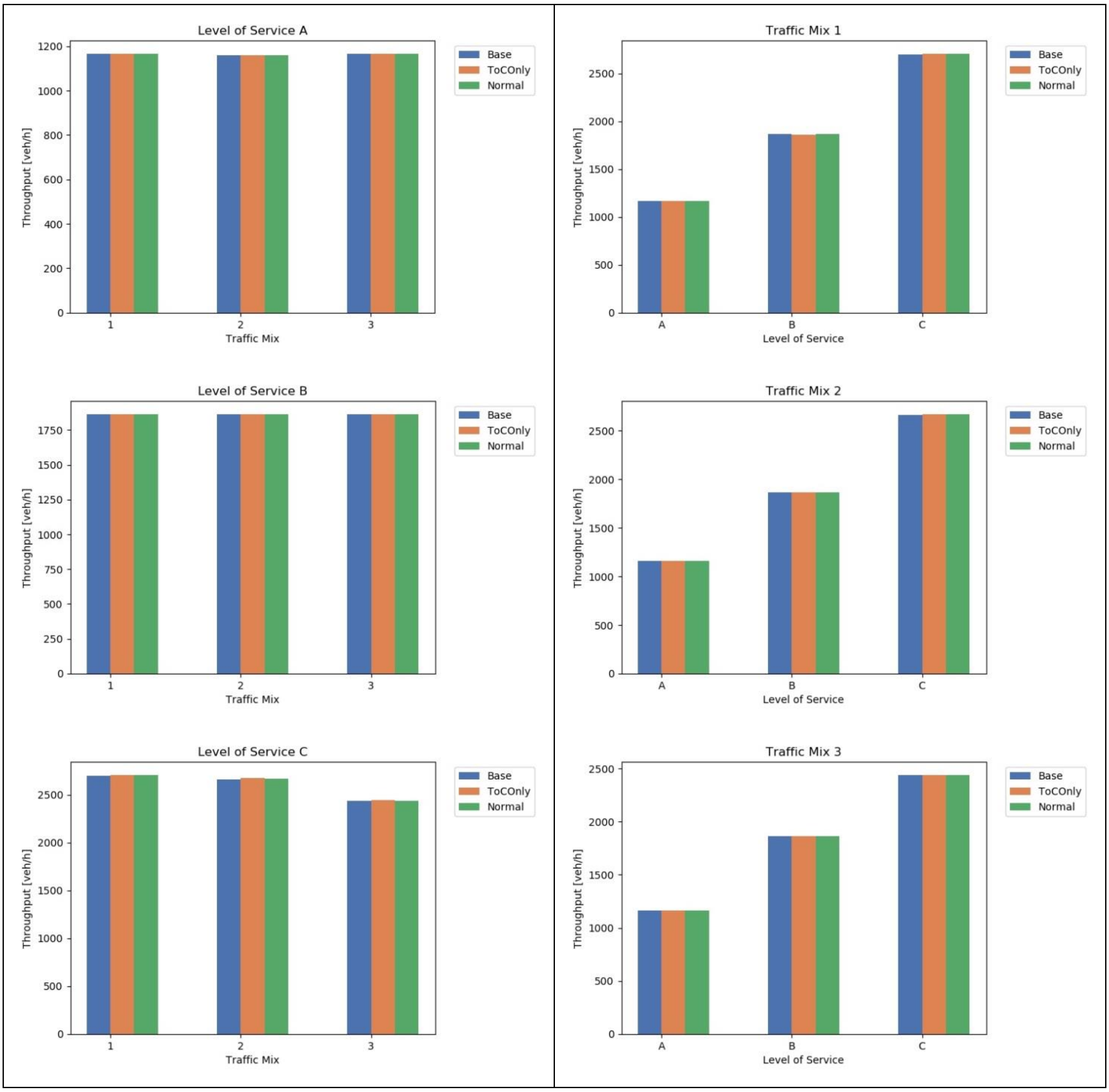


Figure 17: Throughput for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

Local impacts

Under LOS B, vehicle mix 3 (80% C(A)Vs and 20% LVs), and random seed 5, Figure 18 shows speed (upper row) and flow (bottom row) of a 1.5 km road stretch: on-ramp (0~1.0 km) plus acceleration lane (1.0~1.5 km), evolving through time (1 hour) and position. The First Merge Point is at 1.0 km and the acceleration lane starts from 1.0 km until the Lane Drop Point 1.5 km.

The bottom three plots illustrate that the on-ramp flow is relatively low (around 400 veh/h/lane) and they merge into the main road, thus leaving the acceleration lane between the First Merge Point and the Last Merge Point (1.4 km). From baseline to normal (speed advice) scenario, the flow between FMP and LMP is reduced because CAVs on the on-ramp have found a safe merge gap under the traffic strategy of merging assistant.

The upper-left plot of baseline illustrates that the on-ramp speed and acceleration lane speed are mostly free-flow speed until the LMP. CAVs on the on-ramp experienced ToC/MRM due to no gap found and reduced speed between LMP and lane drop point. Once this happens, it raises a safety flag and difficult to recover from the conundrum.

The upper-middle plot of ToCOnly shows some speed reduction between LMP and the Lane Drop Point, thanks to the functionality of the merging assistant issuing ToCs with a prediction horizon.

More speed reduction can be observed in the upper-right plot of the normal (with speed advice) scenario. CAVs on the acceleration lane are instructed according to individual speeds and slow down to merge into the main road. Hence, disturbances of speed are more evenly distributed on the acceleration lane (see the green regions from 1.0 km to 1.4 km).

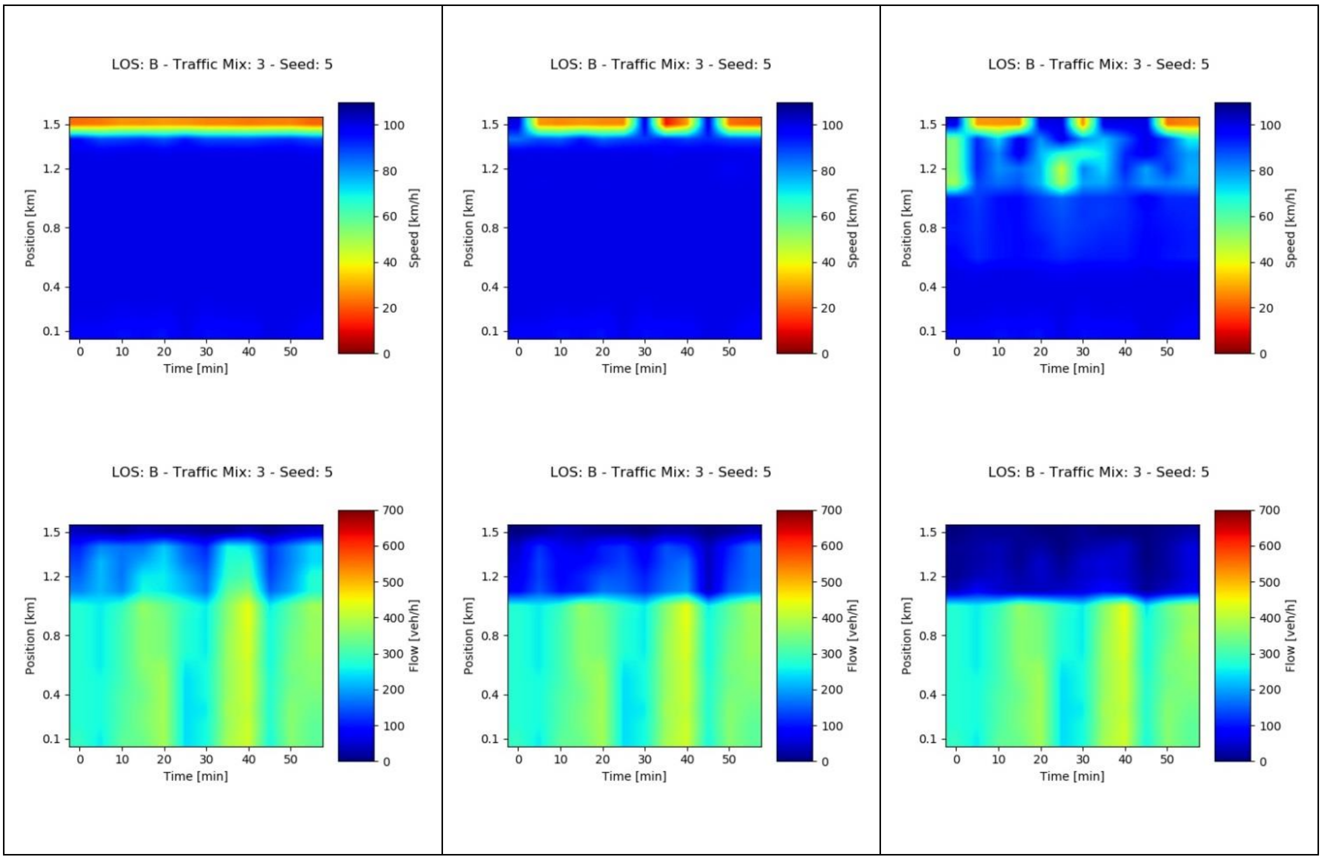


Figure 18: Example time-space-diagrams (on-ramp) of measured speeds (upper row) and flows (bottom row) for baseline (left column), ToCOnly (middle column), and speed advice (right column), for use case 2.1 (LOS B, vehicle mix 3, seed 5).

Figure 19 shows speeds (upper row) and flows (bottom row) of a 2.5 km (0~2.5 km) road stretch: two-lanes (left and right lane) on the main road, evolving through time (1 hour) and position, under LOS B, vehicle mix 3 (80% C(A)Vs and 20% LVs), and random seed 5.

The first merge point is at 1.6 km and the three-lane motorway (including the acceleration lane) starts from 1.6 km until the Lane Drop Point at 2.1 km, which is the merging zone.

The bottom three plots illustrate that the main road flow is mostly below capacity drop under LOS B. Comparing among the baseline, ToCOnly, and normal (speed advice) scenarios, the flow between FMP and LMP is slightly increased and propagated more upstream because CAVs on the on-ramp can now utilise the merge gaps on the mainline more optimally, under the traffic control of the merging assistant. In return, the flow is better distributed on the three-lane, which shows a slightly increased and backwards propagated flow characteristics.

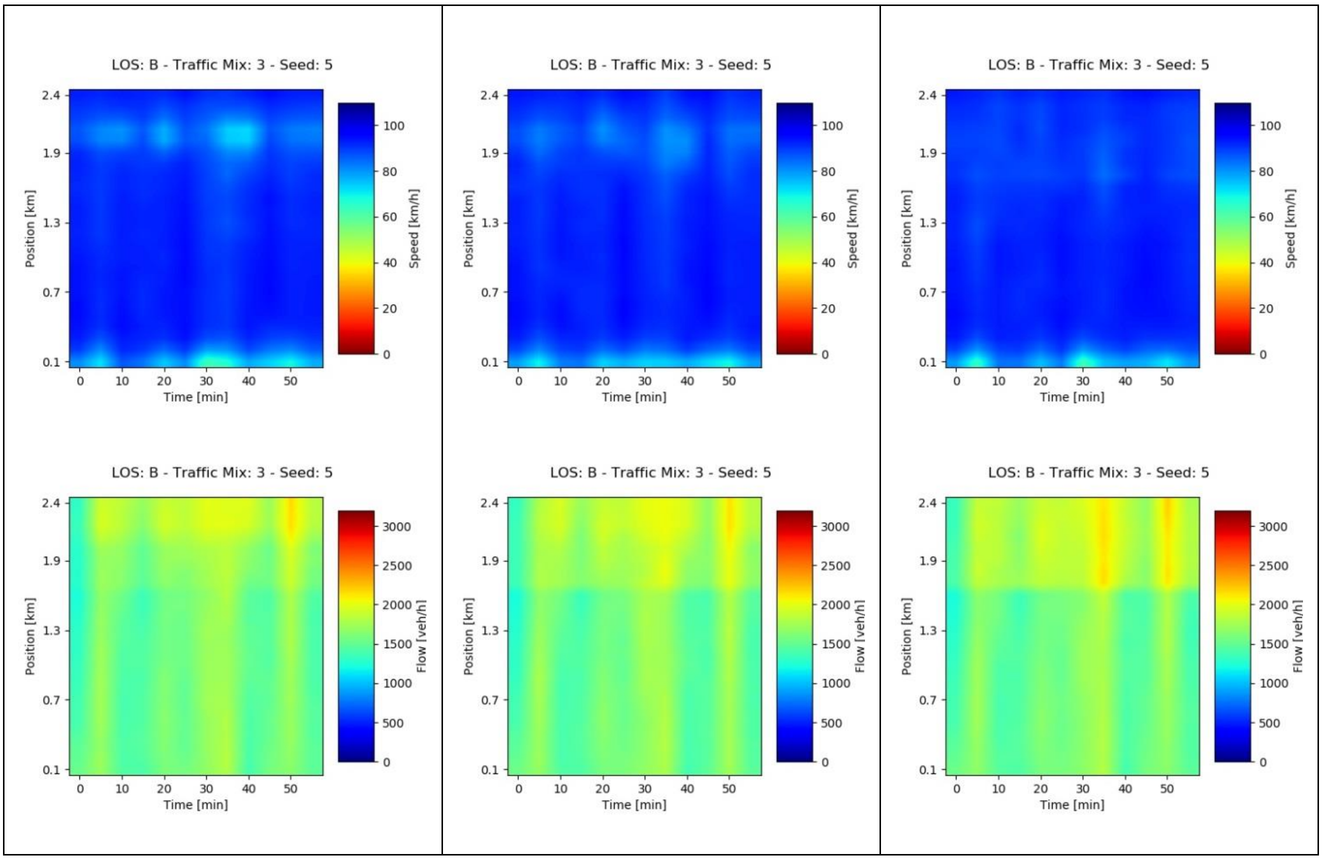


Figure 19: Example time-space-diagrams (mainline) of measured speeds (upper row) and flows (bottom row) for baseline (left column), ToCOnly (middle column), and speed advice (right column), for use case 2.1 (LOS B, vehicle mix 3, seed 5).

3.1.2.3.3 Impacts on traffic safety

Figure 20 shows the number of critical events that have a TTC lower than 3.0 seconds, for baseline, ToCOnly, and normal scenarios, under three traffic demands (LOS A, B, and C) and three vehicle mixes (1, 2, and 3). Note that the scaling of y-axis of critical TTCs may vary for each plot.

The interesting step-wise shape of each plot corresponds with the ToC percentages, shown in Figure 14. This direct relation between ToC and critical event is also established in Deliverable D3.1.

As the traffic demand increases, the number of TTCs increases for all three scenarios: baseline, ToCOnly, and normal. As the vehicle mix changes, conflicting results of lower number of TTCs for baseline and ToCOnly under higher LOS and higher vehicle mixes are shown, comparable to the results of Deliverable D3.1. This is because we have adjusted the on-ramp vehicle demand to half of the corresponding demand, and main road vehicle demand to 5/6 comparing to 2/3 of the three-lane motorway in Deliverable D3.1, to the end of developing merging assistant and thus reflecting a more relaxed traffic situation. Therefore, the main road traffic becomes more homogeneous with less disturbances coming from the on-ramp, consequently leading to less TTC events.

For most of the plots, a positive impact of the merging assistant reducing the number of TTCs can be observed clearly. In the ToCOnly scenario, this effect is also visible, which shows that issuing a ToC earlier by the merging assistant can reduce the number of TTCs. This phenomenon relates to the new ToC method in Service 5 of this deliverable.

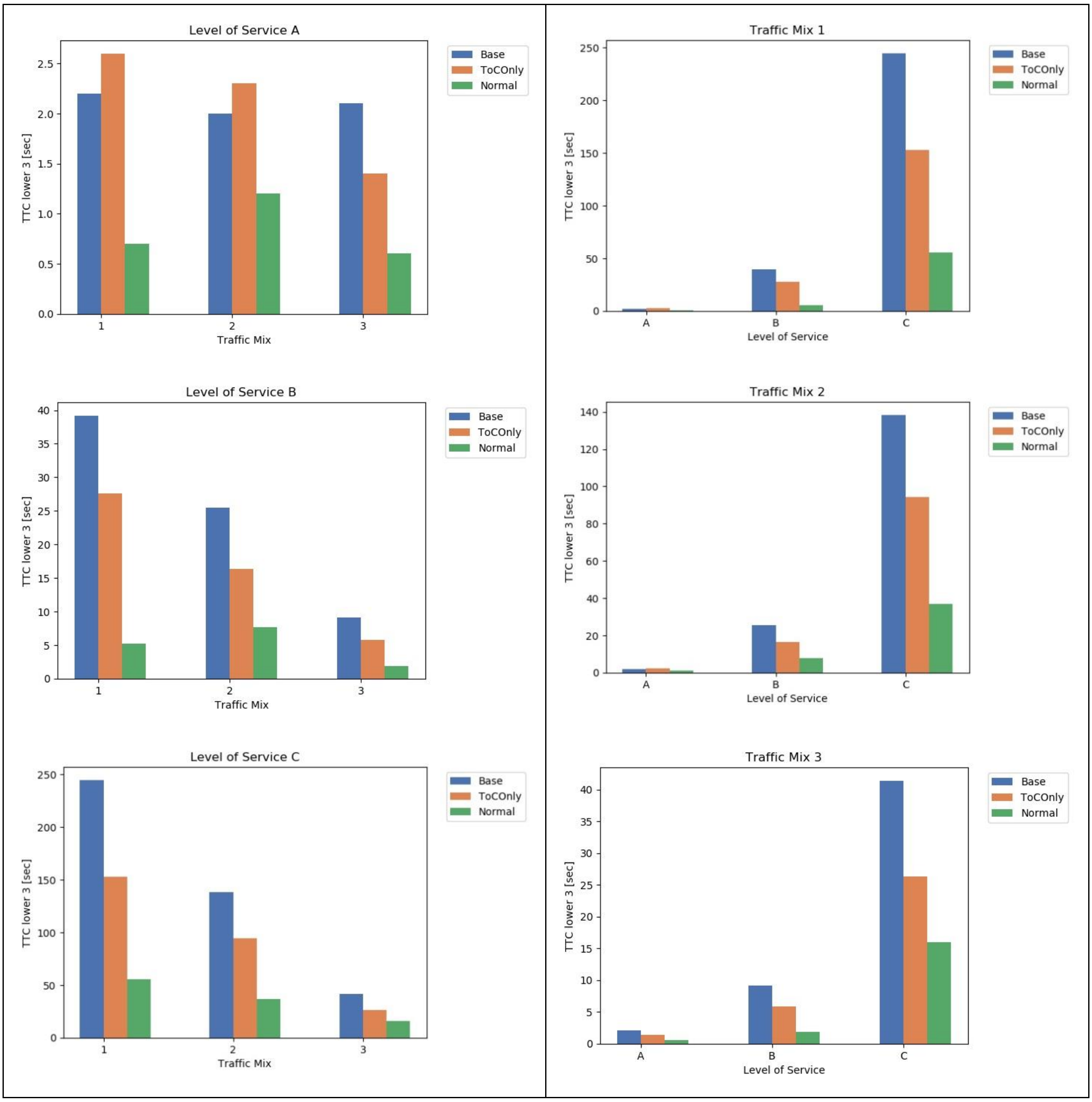


Figure 20: TTC lower than 3 s for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

3.1.2.3.4 Environmental impacts

Figure 21 shows the average CO_2 emissions per travelled kilometre for the baseline, ToCOnly, and normal scenarios, under three traffic demands (LOS A, B, and C) and three vehicle mixes (1, 2, and 3). Note that the scaling of y-axis of CO_2 emissions may vary for each plot.

For each scenario, baseline, ToCOnly, or normal, the average CO_2 emissions increase together with the traffic demands and vehicle mixes. A reduction of average CO_2 emissions can be observed from baseline to ToCOnly, from ToCOnly to normal, in all six bar plots. This shows that the merging assistant has a positive environmental impact when issuing ToCs according to its predictive calculation (ToCOnly) and an even larger positive impact when providing speed advice (normal).

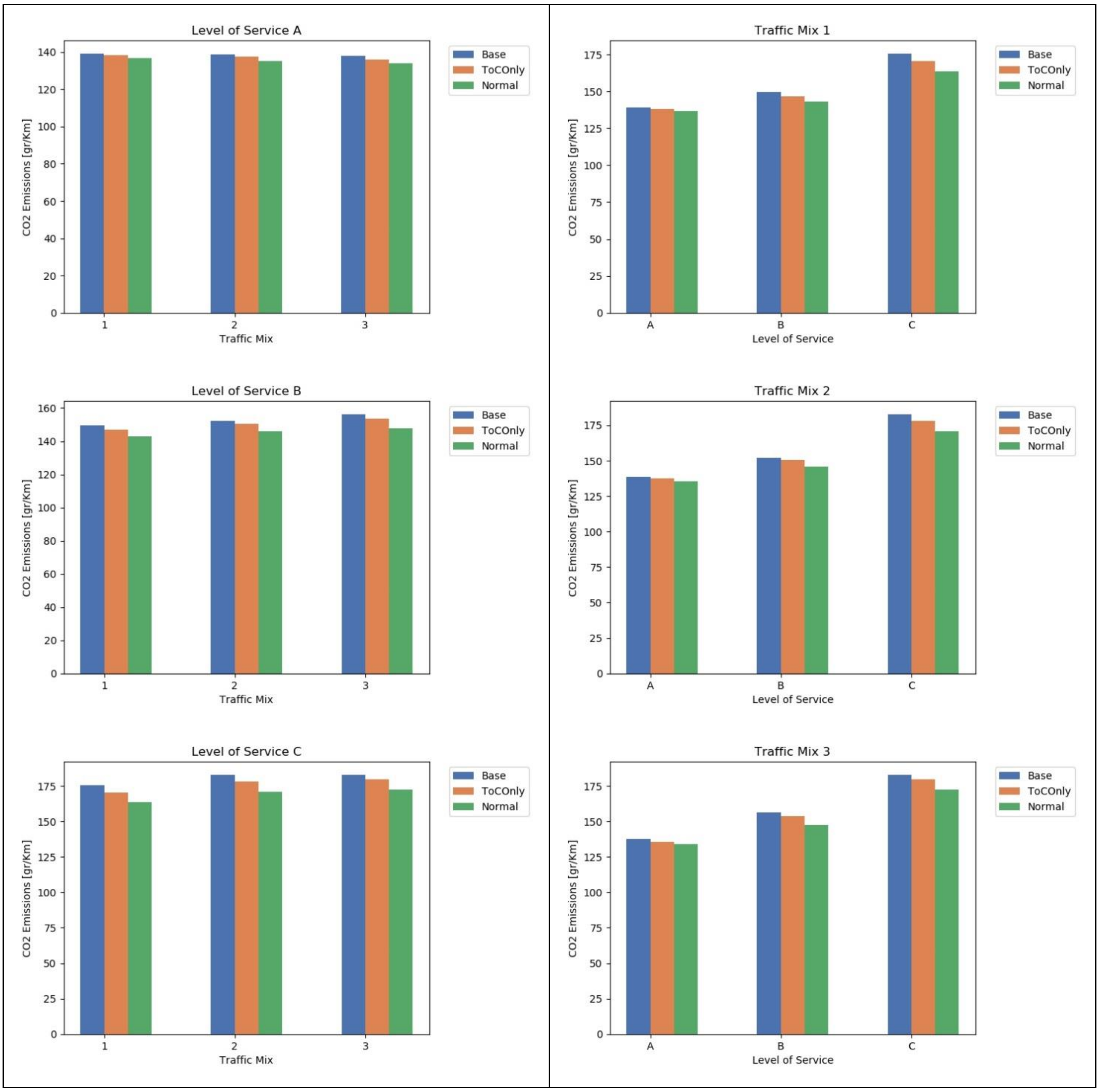


Figure 21: CO_2 emissions for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

3.1.2.4 Discussion

3.1.2.4.1 Conclusion

From the ToC percentages of the 27 scenarios results and vehicle stops data of one scenario (shown in Table 6, Table 7, and Table 8), we draw the following conclusions:

1. A clear conclusion from the results is that infrastructure sensors are vital if there is a significant share of LVs. The model that is based solely on entry detection upstream of the merging area is not accurate enough to find gaps that still exist by the time the vehicle arrives there.
2. As the percentage of CAVs/CVs increases (vehicle mix increases from 1 to 3) under each traffic demand level (LOS A, B, or C), the ToC percentage increases; as the traffic demand level increases (from LOS A to LOS C), the ToC percentage also increases. In Figure 14, the ToC percentage for the baseline shows a steady increase from 51% to 90 %.
3. The vehicle stops of the ToCOnly scenario has decreased approximately 39% compared to the baseline, and the vehicle stops of the normal scenario (with speed advice) has decreased approximately 80% compared to the ToCOnly scenario. This shows that the merging assistant has a positive effect on finding merging gaps and prevents vehicles from full stops on the acceleration lane due to ToCs induced by no imminent merge possibilities.
4. The ToCOnly scenario encompasses the fail-safe of ToC and MRM. This can be implemented with vehicle sensors if the on-ramp and acceleration lane are sufficiently long to still leave space for ToC and MRM. For the ToC percentages in the ToCOnly scenario, we see the same trends in Figure 15. Similar to point 2, the ToC percentages for the ToCOnly scenario show a steady increase from 21% to 61%.
5. With all features of the merging assistant service switched on, we can lower the ToC percentage of the 9 scenarios (3 vehicle mixes × 3 LOS) to a range between 4% and 54%. Higher improvements are shown under low CAVs/CVs penetration rates and low traffic demand. For vehicle mix 1 and LOS A, 80% improvement on the ToC percentage is shown, comparing ToCOnly with MergingAssistant speed advice. While for vehicle mix 3 and LOS C, only 11% improvement on the ToC percentage is shown.
6. The observation of points (2) – (4) cannot be observed in Figure 15 with standard deviations of ToC percentages. It shows various standard deviations for different scenarios, ranging from 1% to 11%. The higher numbers of more than 8% are observed in speed advice scenarios when the traffic demand is as high as LOS C. We can also observe from the simulation that, at such a LOS, there are limited available merging gaps, and on-ramp vehicles are halting and waiting for possible gaps on the acceleration lane. Therefore, the performance of the merging system is highly dependent on the arrivals of vehicle platoons on the main road right lane, hence the high standard deviation.
7. There is a clear correlation between ToC percentage and vehicle stops (from meanVehHalt of E3 detector in the SUMO simulation). It shows that preventing a ToC has a very strong effect on preventing a stop.
8. Cooperative data enables us to conclude that if a ToC is required more in advance, it increases the safety.

3.1.2.4.2 Planned research for the 2nd iteration

During the first iteration we focussed on getting the merging guidance operational, as this is the core strategy of the service. In Deliverable D4.1, other strategies were also listed. Together with other improvements on traffic management strategies, they will be included in the 2nd iteration:

1. Ramp metering will be added as a sub-scenario. It can eliminate the requirement for ToCs completely, when assuming a sufficiently accurate traffic model.

2. The ramp metering also increases the possibilities for traffic management as there will be more opportunities to influence the system on a strategic level. The gap acceptance can be configured in a way to steer the volume ratio of the main road and the on-ramp. This has a very large potential to result in a ramp metering that can operate at a higher traffic volume before causing congestion than the current state-of-the-art ALINEA algorithm.
3. The speed advice for vehicles on the main road mentioned in Deliverable D4.1 will be enhanced to provide gap advice to C(A)Vs. Effectively, this means pairing with another C(A)Vs to create and maintain a gap, towards which the vehicle on the on-ramp will be guided.
4. For the lane advice on the main road, a simplified strategy was created that should be treated as a separate strategy because it also affects LVs. This was the measure to prohibit vehicles on the left lane to go back to the right lane once they are in the influence zone. Therefore, the strategy of actively requesting a C(A)V to move to left lane to create space should still be implemented.
5. Both the gap creation and lane advice on the main road will be connected to the traffic management framework. Gap creation and lane changing should depend on each other if there is sufficient space around the vehicle receiving such advice. The setpoints for ‘sufficient’ in this should be determined at the traffic management layer.
6. The data fusion can be further improved, especially with respect to data intervals. The camera updates every second, the C-ITS messages and the base model every 100 ms. This causes discontinuities in the position that should be fixed.
7. Improve data fusion when it comes to vehicles overtaking each other. The base model should be extended to use information about overtaking.
8. The second iteration of WP3 should result in better models for the merging behaviour, this will enable further calibration of the algorithm of this service.
9. ToCs will be modelled according to the work of WP3, which means the applications have to be integrated. Alternatively, the ToC application could offer an interface that enables other applications to request a ToC for a specific vehicle.

The current developments and plans for the 2nd iteration result in an updated list of strategies as listed in Deliverable D4.1:

a. ToC and MRM fail-safe
   Strategy a. uses merging system to monitor-only the merging area; issue ToC when there is no possible gap. (Correspond to ToC-only scenario, see the scenario set-up description in Table3-5, D4.2)
b. Merging guidance
   Strategy b. issues speed advice of 60km/hr to 100km/hr for each on-ramp CAV/CV, issue ToC when there is no possible gap.
c. Lane advice on the mainline left lane
   Strategy c. prohibit lane change for vehicles on left lane, therefore vehicles on the inner-lane are not allowed to perform lc to outer lane (see Figure 3-2).
d. Cooperative speed advice for gap creation
   Strategy d. gives speed advice on the mainline vehicles to create gaps for mergers.
e. Cooperative lane advice for gap creation
   Strategy e. gives lane advice on the mainline vehicles to create gaps for mergers.
f. Intelligent ramp metering

While traffic management strategies (a) to (c) are implemented in this deliverable with results output, strategies (d) to (f) are optional and planned to be investigated during the 2nd iteration.

Through the development of merging assistant and simulations of all 27 scenarios, the application of traffic management strategies (a) to (f) to the different fleet mixes and levels of service are changed, as shown in Table 9.

Table 9: Traffic management strategies solution under TM 1-3 and LOS A-C (update of D4.1).

Vehicle mix	LOS A	LOS B	LOS C
1	a + b + c	a + b + c + f	a + b + c + d + e + f
2	a + b + c	a + b + c + d + e	a + b + c + d + e + f
3	a + b	a + b + c + d + e	a + b + c + d + e + f

The lane change prohibition is always required, except for low volumes and high penetrations of cooperative vehicles. This prevents model inaccuracies that would cause too many ToCs otherwise. Based on the earlier obtained simulation results, we can give some preliminary predictions. For LOS B, with a large share of LVs, only ramp metering would be effective, while for fleet mixes 2 and 3, probably speed and gap creation are still effective. With LOS C, all strategies should be used. These traffic management strategies ‘recipes’ should be tested out in the future research and 2nd project iteration.

3.1.3 Service 3 (use case 3.1): Prevent ToC/MRM by traffic separation

3.1.3.1 Introduction

Traffic complexities arising at highway merge areas are very likely to induce ToCs in mixed traffic streams. The heterogeneous behaviour of (C)AVs, CVs and LVs can favour traffic situations (e.g., cut-in situations, hard braking events, etc.) that result in system-initiated ToCs from the (C)AVs'/CVs' side. Moreover, AVs have a limited finite view of the surrounding road environment. Thus, they require time to obtain situation awareness along the merge area of two separate highways (as shown in the spatial layout of use case 3.1 in Figure 22).

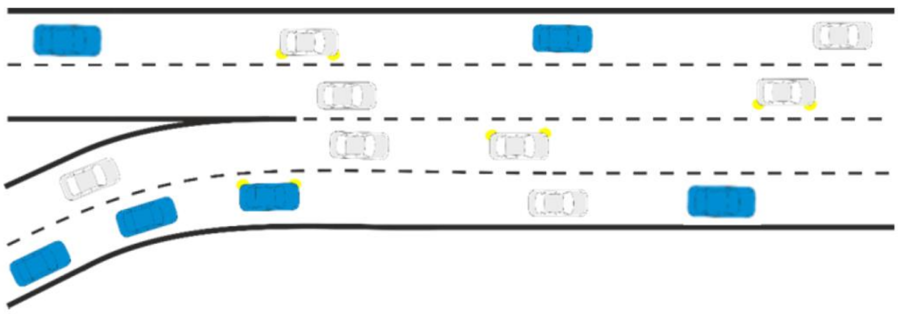


Figure 22: Schematic illustration of use case 3.1.

During this time interval they might encounter urgent situations that they cannot instantly resolve, and need to hand over control back to the driver. This can be challenging for drivers of Highly Automated Vehicles (HAVs) who are allowed to be involved in secondary driving tasks. Hence, driver's irresponsiveness, or reduced performance while taking over control from the vehicle automation, and concurrently regaining situation awareness, can cause traffic turbulence and might lead to safety-critical situations. Homogenising vehicle behaviour upstream of the merge area, and preventing lateral vehicle interactions along the merge area, are actions expected to significantly reduce ToCs and their adverse effects on traffic. A Traffic Separation Policy (TSP) that places (C)AVs/CVs and LVs on separate designated lanes is expected to accomplish the latter objectives. Previously in Deliverable D4.1, we provided initial information regarding the TSP activation pre-conditions, its spatial horizon, and control logic. In the current deliverable, we provide details regarding the determination of the spatial horizon and control logic of the TSP.

3.1.3.2 Traffic management setup

3.1.3.2.1 Description of the areas

3.1.3.2.1.1 Traffic Management Area (TMA)

The TSP implementation requires the definition of the Traffic Management Area (TMA) and the estimation of its spatial horizon, as shown in Figure 23. The TMA encompasses the following subareas:

- Traffic Monitoring Area (TMNA)
- Traffic Separation Area (TSA)
- Transition Area (TA)
- Minimum-Risk Manoeuvre Zone (MRM-Z)

- Merge Area (MA)

The latter categorisation was selected according to the TSP requirements regarding: (a) traffic sensing, (b) communications, (c) advice estimation, provision, and feasibility, and (d) vehicle behaviour. The spatial horizon of the aforementioned areas is estimated in the following subsections.

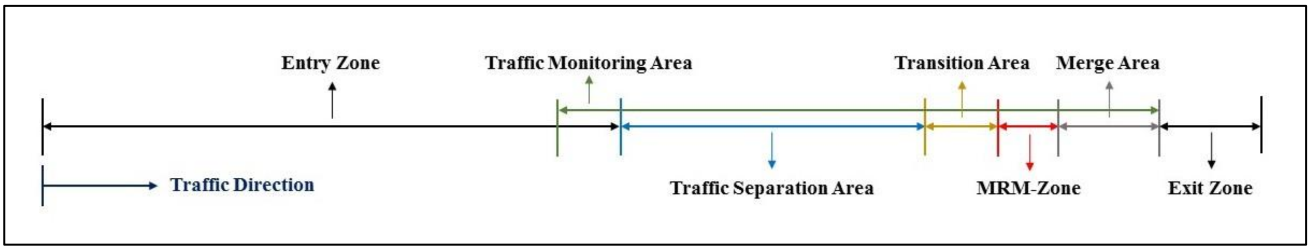


Figure 23: Schematic illustration of the Traffic Management Area (TMA).

3.1.3.2.1.2 Traffic Monitoring Area (TMNA)

The Traffic Monitoring Area (TMNA) practically coincides with the TMA in spatial terms. Traffic sensing and communication equipment is installed along the TMNA to provide real-time vehicle information to the infrastructure for the implementation of the TSP. The TMNA begins 300 m upstream of the Traffic Separation Area (TSA) so that the infrastructure can acquire reliable information about the lane allocation of vehicles, their type, and dynamics. This information allows the infrastructure to determine if lane change advice is necessary for the approaching vehicles, so that the TSP objectives are accomplished. It ends downstream of the Merge Area (MA) where vehicles can make a free lane selection irrespective of their type.

3.1.3.2.1.3 Traffic Separation Area (TSA)

The TSP requires that CAVs/CVs and LVs drive on designated lanes near the highway merge area to minimise vehicle interactions and heterogeneity in behaviour. Vehicles approaching the TSA, which are not located in the predefined target lane according to their type and TSP rules, are provided with lane change advice when they enter the TSA. The execution of the provided advice depends on the available space in the target lane and the status of surrounding traffic.

The lane change distance is a function of the lane change duration, the vehicle speed, and the availability of gaps on the target lane. Previous research by Cao et al. (2013) and Toleda and Zohar (2007) indicated that the average lane change duration for LVs on highways is approximately $\bar{t}_{\mathrm{lc}} = 4.5\,\mathrm{s}$. However, there is currently no relevant information published regarding CAVs/CVs. Considering that the speed limit is set equal to $v_{\mathrm{lim}} = 36.11\ \mathrm{m/s}$ in the highway simulation network of use case 3.1 (see the fact sheets in Deliverables D2.2 and D3.1), LVs travelling with the speed limit require space equal to $\bar{s}_{\mathrm{lc}} = 125\ \mathrm{m}$ to execute the advised lane change manoeuvre.

The highest demand scenario examined in the baseline simulation experiments corresponded to LOS C traffic conditions. In these conditions, the hourly traffic flow rate per lane is equal to $f_{\mathrm{LOS}}\,(C) = 1500\ \mathrm{pcu/h/lane}$ according to the Highway Capacity Manual of the National Research Council (2010). The latter traffic flow rate corresponds to $f_{\mathrm{LOS}}(C) = 50\ \mathrm{pcu/min/lane}$ on a minute basis assuming a uniform vehicle arrival distribution over time. If vehicles are evenly distributed over lanes based on their type (average condition), then 25 lane changes would be required for the implementation of the TSP within a minute. In light of the aforementioned information, and accounting for the non-uniform vehicle arrival pattern, the effect of nearby blocking traffic, and consequently the need for speed adaptation by the ego vehicle to reach the target lane, we empirically assign a length of $s_{\mathrm{TSA}} = 1500$ m to the TSA.

3.1.3.2.1.4 Transition Area (TA)

Although a CAV/CV receives lane change advice for the implementation of the TSP, it is still possible that it cannot execute it due to surrounding blocking traffic. In this case, the CAV/CV should be instructed to initiate ToC at the end of the TSA, so that the driver regains vehicle control when driving in the same lane with LVs. If the ToC is successful then the TSP requirements are fulfilled and the CAV/CV must drive on manual mode in its current lane until the exit from the Merge Area (MA). However, CAV drivers might remain irresponsive until the end of the available lead time (time until MRM) to take over control. Thus, there should be available space downstream of the TSA for the CAV to drive in a 'preparing ToC' state (see Chapter 2.3 in Deliverable D3.1) until the MRM begins. Since the time until MRM was previously set equal to $t_{\mathrm{MRM}} = 10$ s, and the speed limit is $v_{\mathrm{lim}} = 36.11\ \mathrm{m/s}$, the TA should stretch approximately $s_{\mathrm{TA}} = 360$ m.

3.1.3.2.1.5 Minimum-Risk Manoeuvre-Zone (MRM-Z)

If ToC fails and the CAV enters the MRM-Z, then braking is applied so that the CAV comes to a full stop. It is critical that the CAV stops upstream of the merge area to prevent disruption on the traffic flow of the merging highway. For derivation of the braking distance we refer to the reasoning elaborated in Section 2.2.2.2. Assuming a buffer to prevent a full vehicle stop just upstream of the merge area, the MRM-Z is extended to $s_{\mathrm{MRM-Z}} = 300$ m.

3.1.3.2.1.6 Merge Area (MA)

The TSP spatial horizon is also extended downstream of the Merge Area (MA) to allow vehicles of the two merging traffic streams to acquire increased situation awareness of surrounding traffic prior to making lane changes. Thus, traffic flow can remain stable for a significant distance downstream of the MA. Moreover, the initiation of lateral vehicle interactions further downstream of the MA ensures that possible traffic disruption due to the latter reason will not easily propagate and affect traffic operations on the MA unless traffic breakdown occurs. The TSP is finally enforced along a distance of $s_{\mathrm{MA}} = 500$ m downstream of the MA.

3.1.3.2.2 Baseline scenario adaptation

According to the baseline network configuration of Scenario 3.1, the length of the two merging highways upstream of the MA was set equal to $\boldsymbol{s_{\mathrm{upstream}} = 500\ \mathrm{m}}$. However, this length cannot accommodate the needs of the TSP, since it was previously determined that the TMA should span at least $\boldsymbol{s_{\mathrm{TMA}} = s_{\mathrm{TMNA}} + s_{\mathrm{TSA}} + s_{\mathrm{TA}} + s_{\mathrm{MRM-Z}} + s_{\mathrm{MA}} = 2960\ \mathrm{m}}$ (see also Table 10). Thus, the network configuration is adapted to meet the needs of the TSP by extending the highways' length upstream of the MA to $\boldsymbol{s_{\mathrm{upstream}} = 5000\ \mathrm{m}}$. The respective changes in the fact sheets of Service 3.1 are highlighted in yellow in

Table **11**. The extended highway stretches upstream of the MA are also expected to facilitate the stabilisation of the entering traffic flows in the network prior to arrival to the TMA.

Table 10: Spatial horizon of the TSP.

Area	Distance (m)
Traffic Monitoring Area (TMNA)	2960
Traffic Separation Area (TSA)	1500
Transition Area (TA)	360
Minimum-Risk Manoeuvre Zone (MRM-Z)	300
Merge Area (MA)	500
Traffic Management Area (TMA)	2960

Table 11: Adapted network configuration details for Scenario 3.1. Adaptations in yellow.

Scenario 3.1	Settings	Notes
Road section length	2.3 km → 6.8 km	• for each motorway
Road priority	9	
Allowed road speed	36.11 m/s	130 km/h
Number of nodes	5	• n0 – n5
Number of edges	4	
Number of start nodes	2	• n0, n4
Number of end nodes	1	• n3
Number of O-D relations	2	• From n0 to n3 • From n4 to n3
Number of lanes upstream of the merging area	2	
Number of lanes downstream of the merging area	4	• from n1 to n2
Merging area length	1.3 km	
Filename	• network: UC3_1.net.xml	
Intended control of lane usage There is no control on lane usage. In the sub-scenario 1, Based on the RSI provided traffic separation policy, CAVs and CAV Platoons move to the left lane of the left 2-lane motorway and to the right on the right 2-lane motorway some point upstream of the merging point. CVs move to other lanes than the CAVs and CAV Platoons. CAVs and CAV Platoons thus enter the 4-lane section on the outer lanes, giving space to other		

vehicle types to merge.
Network layout 
Road segments n0→n1: Insertion and backlog area (500 m → 5000 m) n4→n1: Insertion and backlog area (500 m → 5000 m) n1→n2: Merging area (1300 m) n2→n3: Leaving area (500 m)

3.1.3.2.3 Traffic separation logic

The control logic of the TSP is comprehensively presented in Figure 24. CAVs/CVs are monitored throughout the TMA and receive personalised advice regarding their designated lane or the need for initiating a ToC. The control logic of the TSP encompasses instructions for cooperative manoeuvring when surrounding vehicles are CAVs and CAV lane changing is not feasible otherwise. However, we do not test this logic within the context of Deliverable D4.2, since we will examine it within the activities of WP3 (Deliverable D3.2). On the other hand, LVs are informed regarding their designated lane at the entrance of the TSA with the use of Variable Message Signs (VMS). Vehicle behaviour under the TSP is explicitly described per vehicle type in the following subsections.

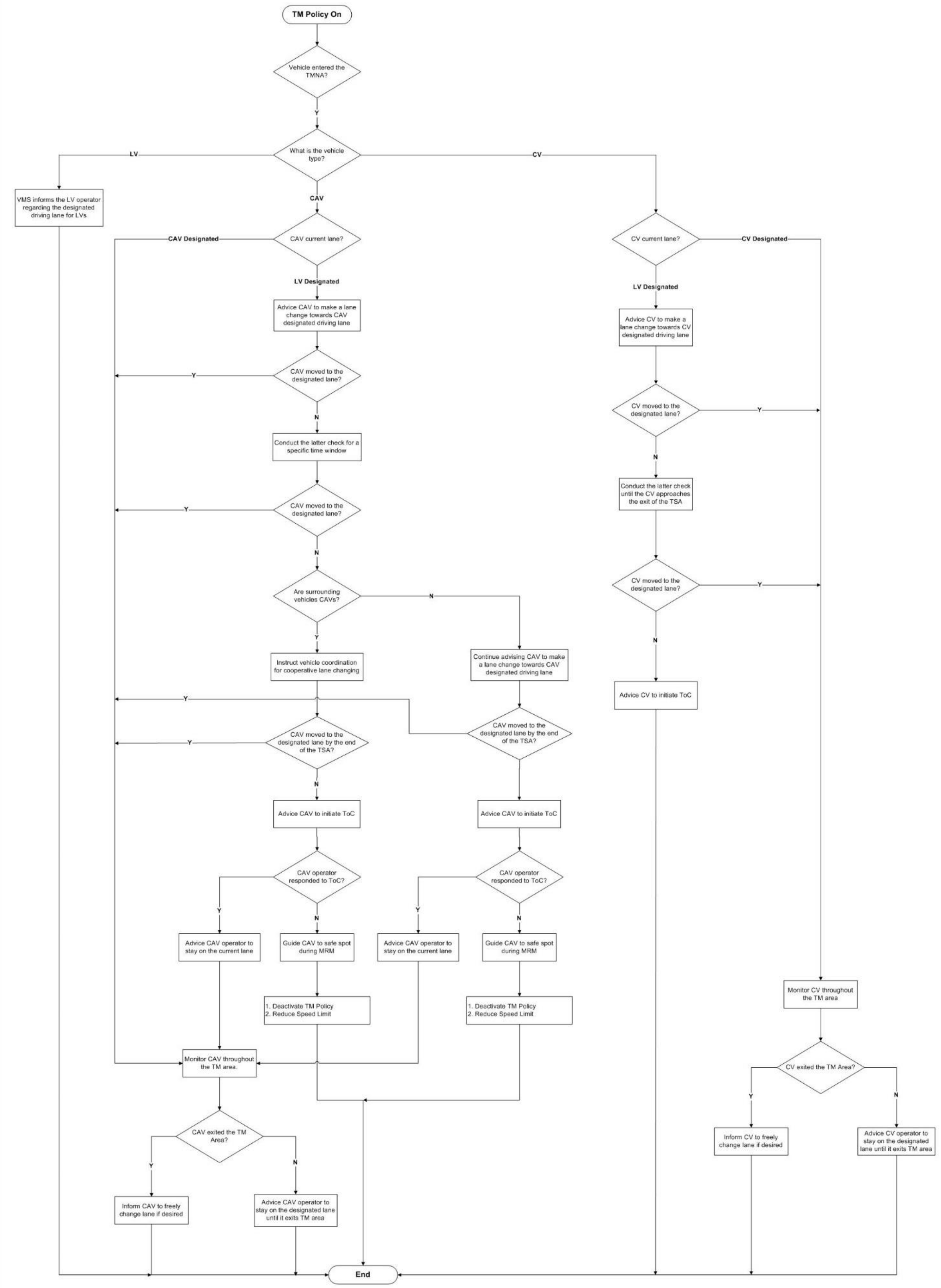


Figure 24: Traffic Separation Policy (TSP) control logic.

3.1.3.2.3.1 CAV behaviour

The TMC determines the lane allocation of approaching CAVs in the beginning of the TMNA. According to the TSP rules, CAVs travelling on the designated CAV/CV lane are requested to remain in the current lane until they exit the TMA. On the contrary, CAVs travelling on the LV designated lane are instructed to change lane to the CAV/CV designated one. In case CAVs are blocked by traffic in the CAV-designated lane and cannot change lane freely, they cannot adapt their speed to catch an acceptable gap for lane changing. CAV cooperation is not addressed in this deliverable as explained previously. If CAVs manage to reach their designated lane prior to the TSA exit point, then the TSP is successful as shown in Figure 25. CAVs subsequently receive information to drive freely at the end of the TMA (downstream of the MA). However, if a CAV fails to change lane to the CAV/CV-designated one throughout the TSA, then the RSI instructs a ToC initiation. In the case of successful take-over from the CAV operator, the RSI advises the driver to continue driving manually on the LV-designated lane until the TMA is exited. Then, it is assumed that the TSP is not disrupted and can remain active. On the other hand, if the driver fails to respond to the system-initiated take-over request, then the vehicle automation executes an MRM. If this MRM brings the vehicle to a full stop, then the TSP is deactivated and the speed limit is reduced on the TMA to prevent safety-critical situations and to stabilise/homogenise the traffic flow (see also Figure 26).

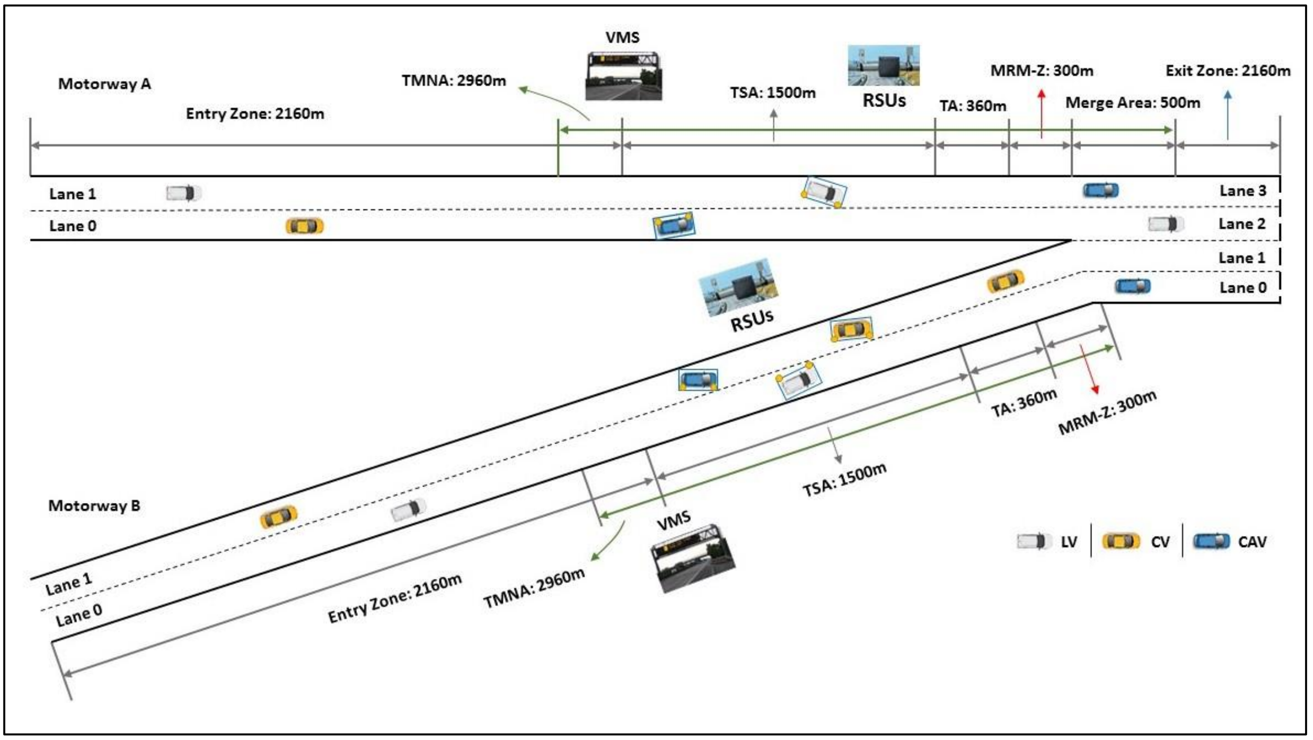


Figure 25: Successful implementation of Traffic Separation Policy.

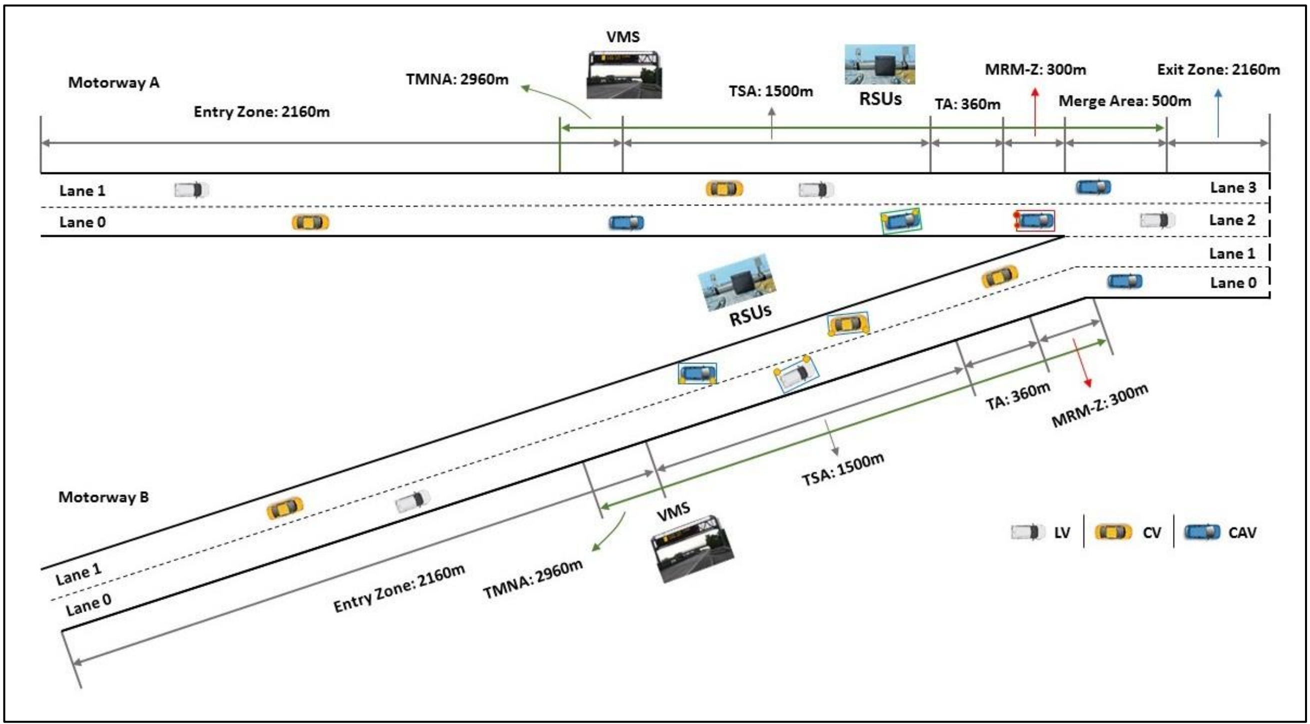


Figure 26: Traffic Separation Policy disrupted by Minimum-Risk Manoeuvre (MRM).

3.1.3.2.3.2 CV behaviour

CVs can also receive advice to either remain in their current lane or change lane depending on their driving lane along the TMNA. However, the driver is responsible for executing the provided advice in the case of CVs. In this research, we assume that the compliance rate of the CV operators to the RSI advice is 100%. CVs can adapt their speed to move to the CAV/CV-designated lane if they are blocked by surrounding vehicles. However, if a CV fails to reach the target lane by the end of the TSA, then the RSI instructs a ToC. In this case, the CV operator is always assumed to take over vehicle control successfully, since CV drivers are expected to continuously monitor the primary driving tasks. Thus, CVs cannot disrupt the TSP within the context of the TransAID traffic management simulation experiments. Finally, CVs exiting the TMA are informed about the end of the TSP by the TMC and can freely select their desired driving lane.

3.1.3.2.3.3 LV behaviour

Lane allocation of LVs is also monitored upstream of the TSA. LVs are instructed about their designated lane with the use of VMSs and have to act accordingly (either stay on current lane or change to the LV-designated lane). We assume that LVs will be able to reach the target lane within the TSA in any case, since they can significantly adapt their behaviour (reduce speed or accept shorter gaps) to implement the TSP. LVs are also informed about the end of the TSP with the use of VMSs downstream of the MA.

3.1.3.3 Results

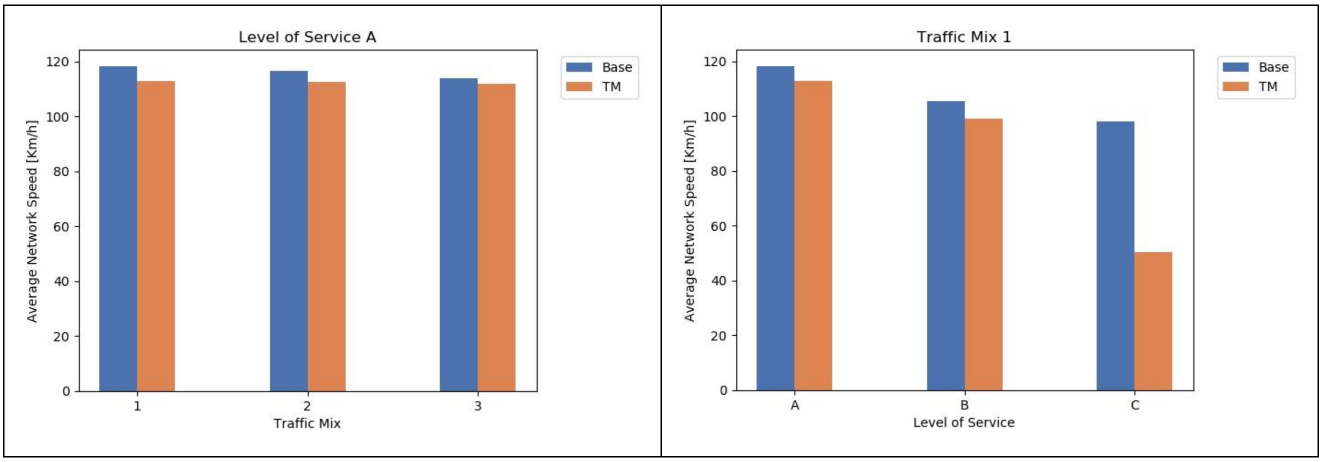
3.1.3.3.1 Impacts on traffic efficiency

Network-wide impacts

The average network speed results presented in Figure 27 indicate that during baseline simulations free-flow traffic conditions prevail on the simulation network of use case 3.1. These results are in alignment with the relevant findings previously described in Deliverable D3.1. The ToC effects on traffic are not critical enough to generate a breakdown given the adopted ToC modelling approach of Mintsis et al. (2018). Moreover, the assumption of no full vehicle stops after MRMs prevents excessive traffic turbulence as well. Thus, there was limited potential for improvement for the traffic separation policy that mainly concerned higher demand levels and increased shares of CAVs (vehicles performing ToCs/MRMs).

However, results show that average network speed slightly decreases for all tested traffic demand levels and vehicle mixes when the traffic separation policy is implemented. This phenomenon occurs due to the following two reasons.

1) Initially, different vehicle types exhibit different car-following and lane-change behaviour. LVs were modelled to be more aggressive, while C(A)Vs were more conservative. Therefore, when the TMC instructs lane changes for the implementation of the traffic separation policy, several LVs cut in just in front of CAVs in order to reach the advisable lane. This behaviour results in excessive braking from CAVs, which exhibit higher desired car-following time headways, which in turn causes multiple shockwaves along the traffic separation area. It can be seen that for higher shares of LVs, the speed reduction becomes more prominent. When traffic demand increases as well (going to LOS C), the implementation of traffic separation results in a traffic breakdown.
2) There is excessive lane changing occurring downstream of the traffic management area. Vehicles leaving the traffic management area are allowed to freely choose their desired driving lane. Thus, the implementation of several lane changes within a short spatial horizon results in traffic disruption and eventually speed drop.



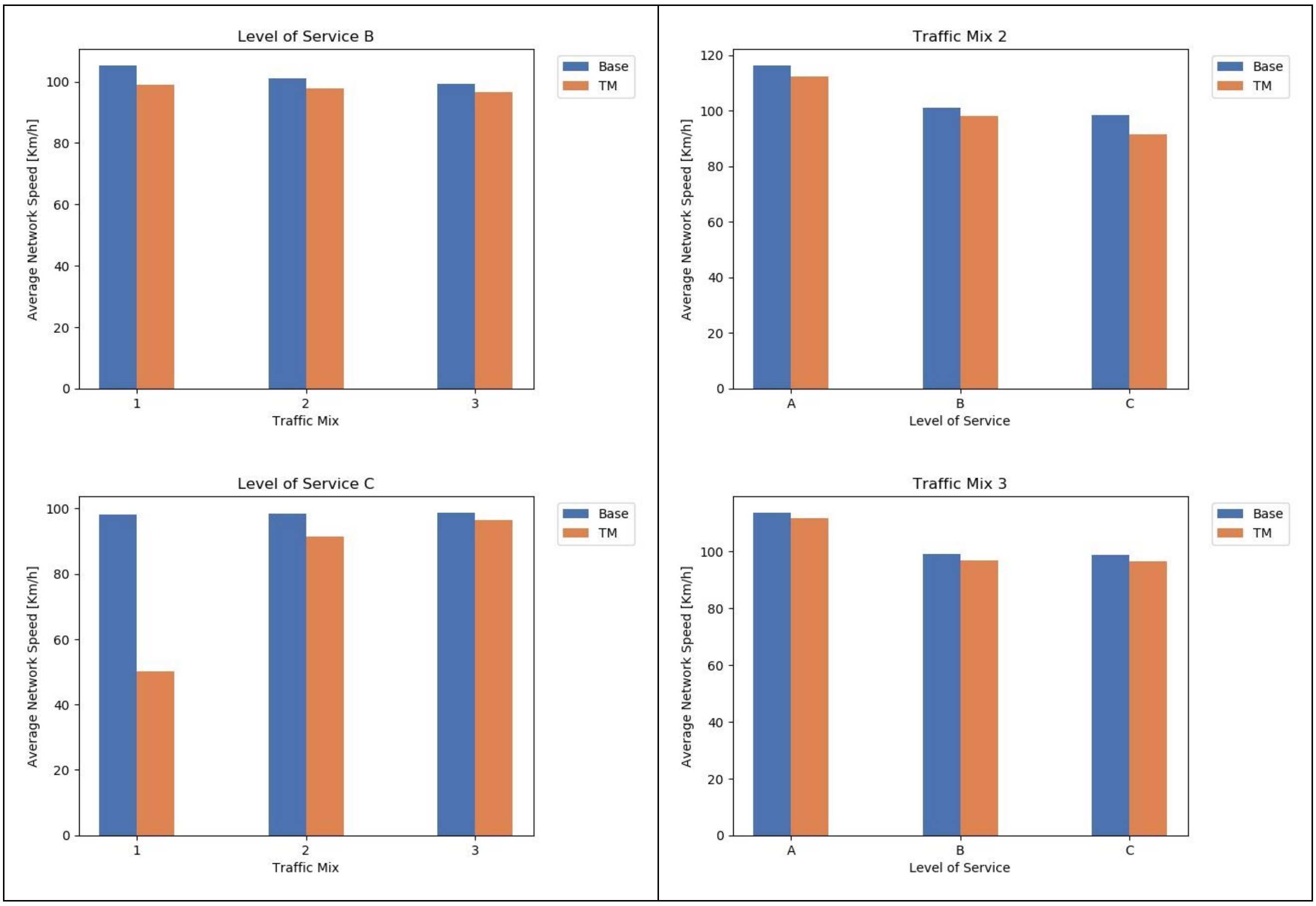


Figure 27: Average network speeds for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Although the average network speed is always higher for the baseline case, throughput benefits can be observed for the traffic separation case (see also Figure 28) when traffic demand increases (LOS B and LOS C) and the CAV share is higher in the fleet (vehicle mixes 2 and 3). Except for LOS C and vehicle mix 1, when LVs lane change behaviour generates excessive congestion, it can be seen that throughput slightly increases for the other LOS C cases (vehicle mixes 2 and 3) and LOS B, vehicle mix 3. In the baseline simulations of the latter cases, the occurrence of multiple ToCs along the merge area results in speed reductions that are more significant compared to the traffic management case. This can be observed in the following speed tempo-spatial contour plots depicted in Figure 29. Thus, lesser vehicles manage to exit the simulation network within an hour. For the rest of the examined cases, the throughput is similar between the baseline and the traffic management case.

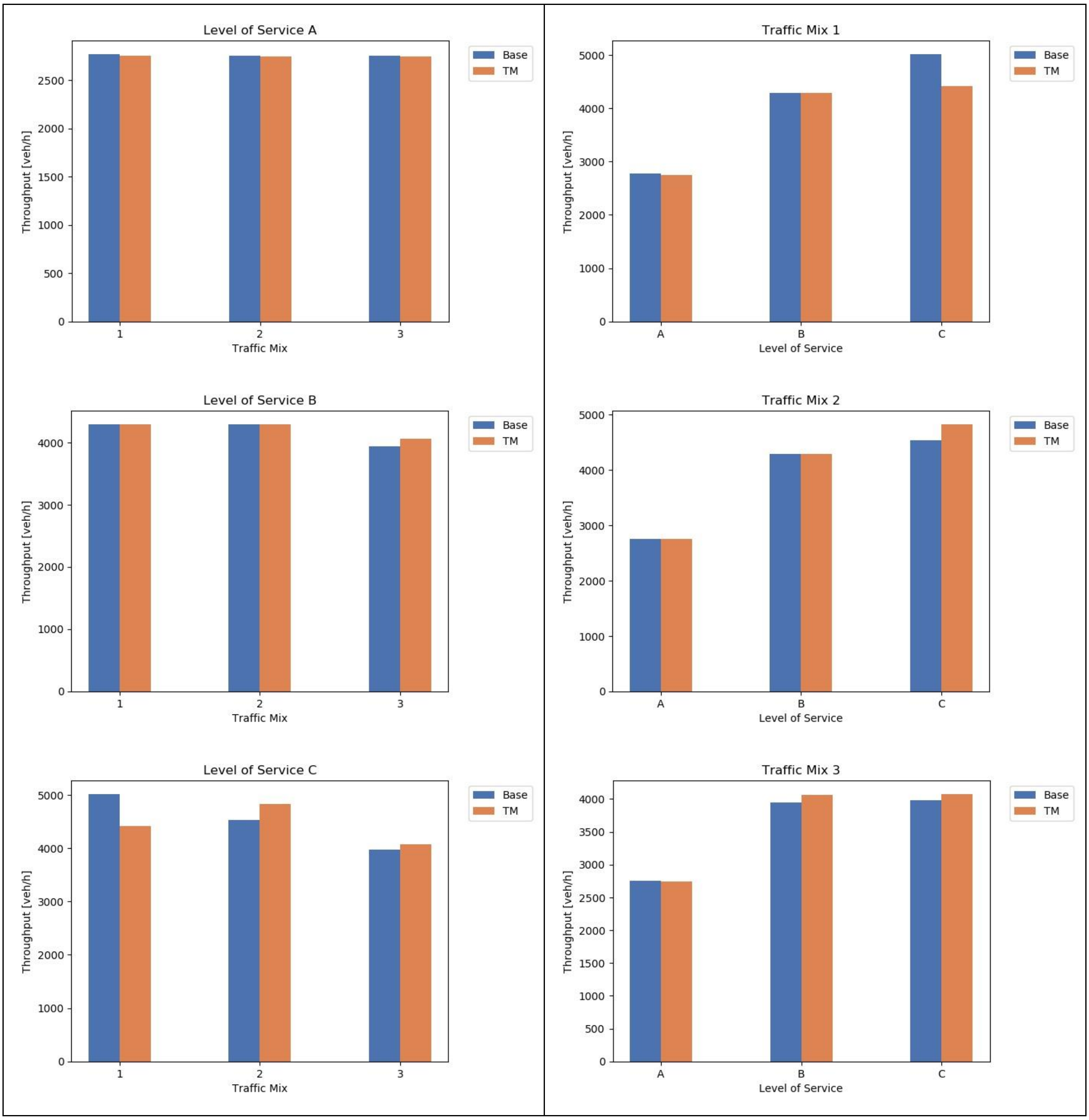
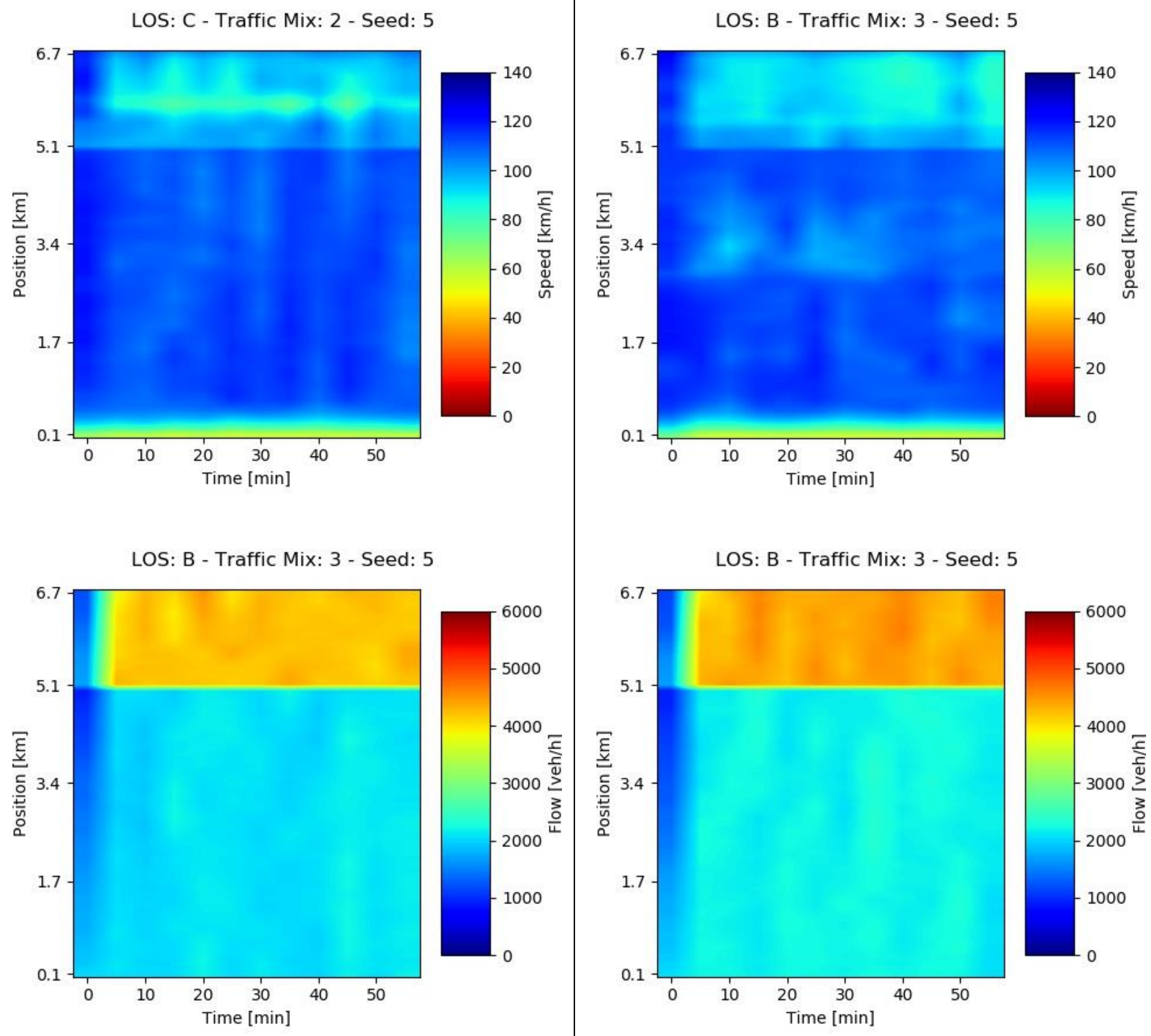


Figure 28: Throughput for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Local impacts

Example speed and flow tempo-spatial contour plots regarding LOS C, vehicle mix 3, seed 5 are presented in Figure 29, both for the baseline and the traffic management case. As previously discussed, the source of the traffic disruption differs between the two cases. In the baseline case, traffic disruption results from ToCs/MRMs occurring downstream of the merge area (cf. upper left plot of Figure 29). In the traffic management case, traffic disruption stems from cut-in situations occurring along the traffic separation area and dense lane change activity taking place downstream of the traffic management area (cf. upper right plot of Figure 29). The speed tempo-spatial plots for the baseline and the traffic management case justify previous results regarding average network speed and throughput. Although the speed drop areas are more frequent in the traffic management case, the intensity of traffic disruption due to ToCs/MRMs at the end of the simulation network in the baseline case is higher, and thus throughput slightly decreases (lower plots of Figure 29).



Baseline scenario | **Service 3**

Figure 29: Example speed and flow tempo-spatial diagrams for use case 3.1 (LOS B, vehicle mix 3). The left column corresponds to the baseline scenario and the right column to the traffic management (Service 3) scenario.

3.1.3.3.2 Impacts on traffic safety

Traffic safety deteriorates for most of the examined scenarios (varying traffic demand levels and vehicle mixes) when traffic separation is applied (see also Figure 30). As mentioned before, LV lane change activity generates traffic disruption both along the traffic separation area and downstream of the traffic management area. In these cases, cut-in situations cause more safety critical events compared to ToCs/MRMs. When the share of LVs is higher in the vehicle mix, this phenomenon occurs for all traffic demand levels. However, when the share of C(A)Vs in the simulated fleet increases, occasions occur when ToCs/MRMs generate more safety-critical events, since cut-in situations are reduced due to the decreased penetration rate of LVs.

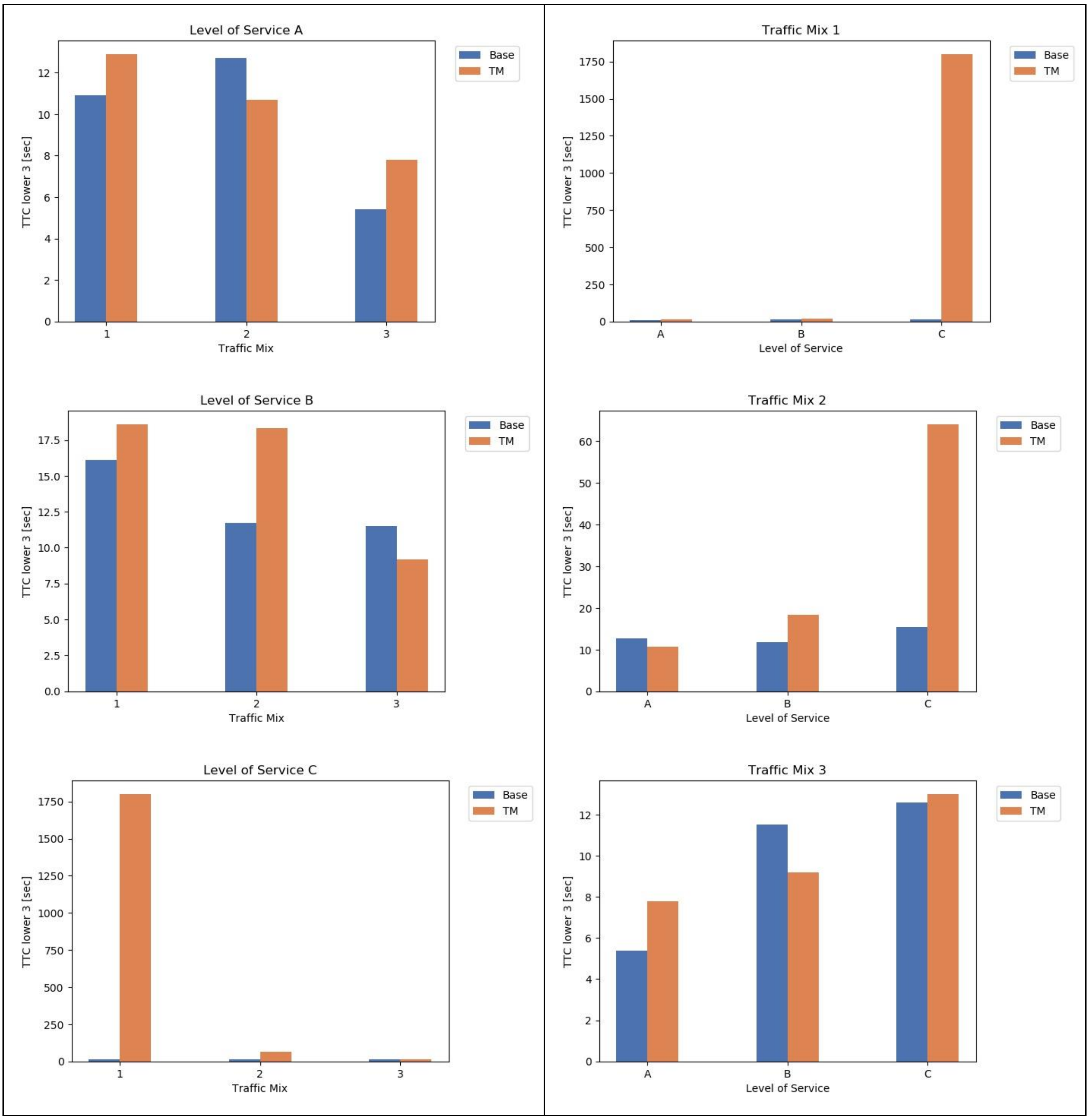


Figure 30: Average number of safety-critical events (TTC < 3.0 s) for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

3.1.3.3.3 Environmental impacts

CO_2 emissions differ marginally between the baseline and the traffic separation case, except for simulation scenarios corresponding to LOC C and vehicle mix 1 (see also Figure 31). As previously explained, congestion prevails in the latter case when traffic separation is applied, due to cut-in situations occurring from LV lane change behaviour. Thus, CO_2 emissions increase significantly when the share of LVs is high and traffic demand is medium (LOS C). On the other hand, CO_2 emissions are slightly higher for the baseline case when the rest of the simulation scenarios (traffic demand levels and vehicle mixes) are considered. These latter findings also comply with average network speed plots presented in Figure 29.

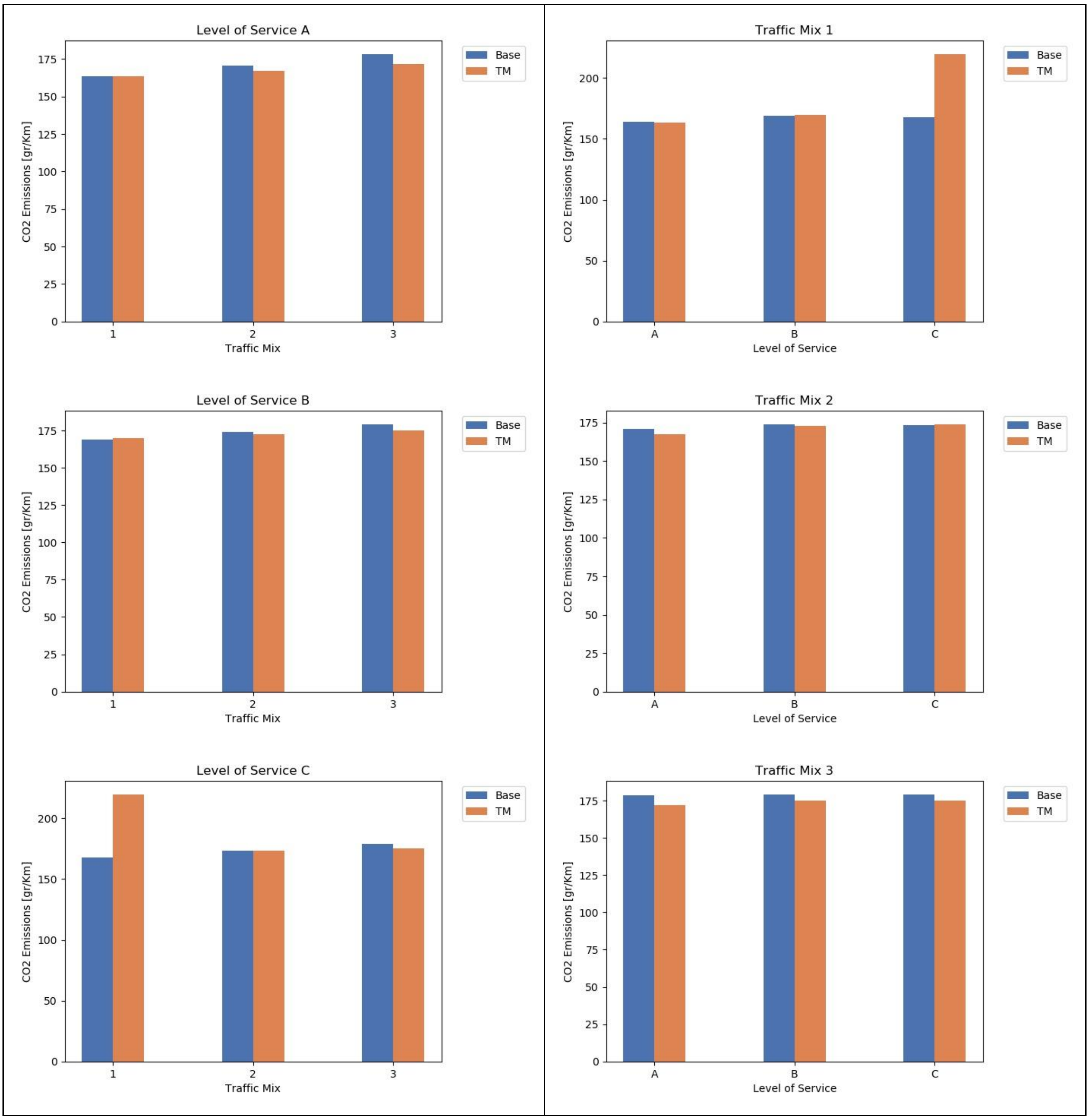


Figure 31: Average CO_2 emissions per kilometre travelled for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

3.1.3.4 Discussion

Simulation results for use case 3.1 indicate that the average network speed is always higher for the baseline simulation scenarios compared to the traffic management ones. Traffic turbulence occurring from LV lane change activity (cut-in situations) along the traffic separation area, and dense lane change activity downstream of the traffic management area, where vehicles are free to choose their desired driving lane, is responsible for the observed speed drop during the traffic separation simulations. Considering that the average network speed is already close to the speed limit for baseline simulations, there is limited room for improvement in terms of traffic efficiency. Thus, improvement might be possible when cooperative manoeuvring is applied to facilitate the CAV lane changing, and lane changes downstream of the traffic management are distributed in space and time.

However, it was identified that the throughput can be higher for the traffic separation case when the share of C(A)Vs increases in the vehicle mix and traffic demand is increasing from low to medium (LOS B and C). In these cases, the traffic disruption occurring during the baseline simulations at the merge area is more intense compared to that incurred form cut-in situations and intense lane activity taking place along the traffic separation area and downstream of the traffic management area during the traffic separation simulations respectively (speed and flow spatiotemporal plots of Figure 29). Moreover, it was demonstrated that cut-in situations caused by LVs lane changing increase safety-critical events, as CAVs need to brake hard to avoid collisions and maintain their desired car-following time headway, which is more conservative compared to manual driving. Thus, it is critical that in future simulations, the lane change model is calibrated for LVs to ensure the credibility of the aforementioned results. Finally, it was shown that CO_2 emissions differ slightly between the baseline and the traffic separation case.

3.1.4 Service 4 (use case 4.2): Manage MRM by guidance to safe spot (urban & motorway)

3.1.4.1 Introduction

Work zones are expected to disrupt vehicle automation by inducing vehicle disengagements. Ambiguous lane markings and complex traffic situations (e.g., merging) can be challenging for AVs, and result in system-initiated ToCs from the AV side. In this case, the vehicle operator is expected to take over control and manually drive the AV past the work zone (until a higher level of automation is feasible again). However, drivers of HAVs might be involved in secondary driving tasks and fail to respond in a timely manner (within the available time budget) to the TOR. Thus, AVs will execute an MRM to bring the vehicle to a full stop until the driver regains control. Unless these MRMs are guided to safe spots upstream of the work zone (see also Figure 32), their negative impacts on safety and traffic efficiency are expected to be significant. The TMC can be made aware of the AV status (e.g., a vehicle's location and speed, driving mode, and ToC status) using V2I communications and intervene when MRM becomes foreseeable to guide the AV to a predefined safe spot. TMC instructions could encompass both longitudinal and lateral guidance to safe spots. We assume that HAVs will be capable of lane changing during MRMs.

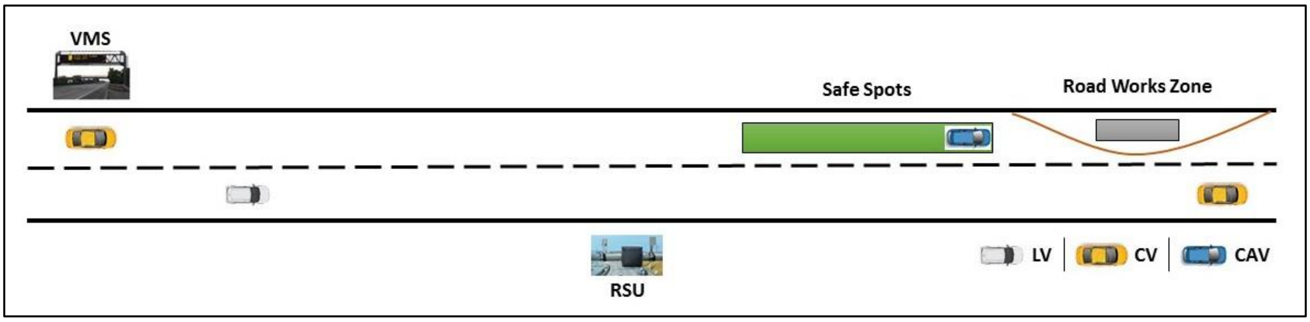


Figure 32: Safe spots upstream of road works zone.

3.1.4.2 Traffic management setup

3.1.4.2.1 Baseline scenario adaptation

In the baseline simulation experiments, conducted within the context of Deliverable D3.1, our focus was mainly put on the analysis of MRMs that do not necessarily result in full vehicle stops. Although we found that these types of MRMs undermine safety and traffic efficiency, there is limited potential for management since drivers regain vehicle control prior to the full stop. Hence, there is practically no incentive to guide the vehicle to a full stop at a designated location. On the contrary, traffic management can yield significant benefits when MRMs lead to full vehicle stops. In this case, the TMC can reserve a predefined safe spot upstream of the work zone and instruct an MRM towards this safe spot. Thus, we can prevent an unexpected vehicle stop at an undesired and sub-optimal location.

Therefore, the baseline simulation experiments are adapted by parametrising the ToC model ($driverResponseTime = 300$ s) to replicate a full vehicle stop after an MRM on the outermost lane (in the proximity of the work zone). The AV will remain stopped for a significant amount of time on the open lane inducing safety-critical events and significant delay to upstream traffic. On the other hand, the implementation of the TransAID Service 4 'Manage MRM by guidance to safe spot' leads the AV safely to the first available safe stop upstream of the work zone. The details of the latter service are described in the following section.

3.1.4.2.2 Traffic management logic

The control logic of TransAID Service 4 is comprehensively presented in Figure 33. The RSI monitors the area upstream of the work zone and is continuously informed about the CAVs' locations, dynamics, and driving mode. When a system-initiated TOR is issued by a CAV, the TMC becomes aware of the situation and checks if a safe spot is available to guide the CAV in case of an MRM. Concurrently the TMC assesses the CAV's distance from the safe spot and determines its driving lane. According to the availability of safe spots, the latter distance, and the CAV driving lane, the TMC determines the instructions for guiding the MRM to the safe spot.

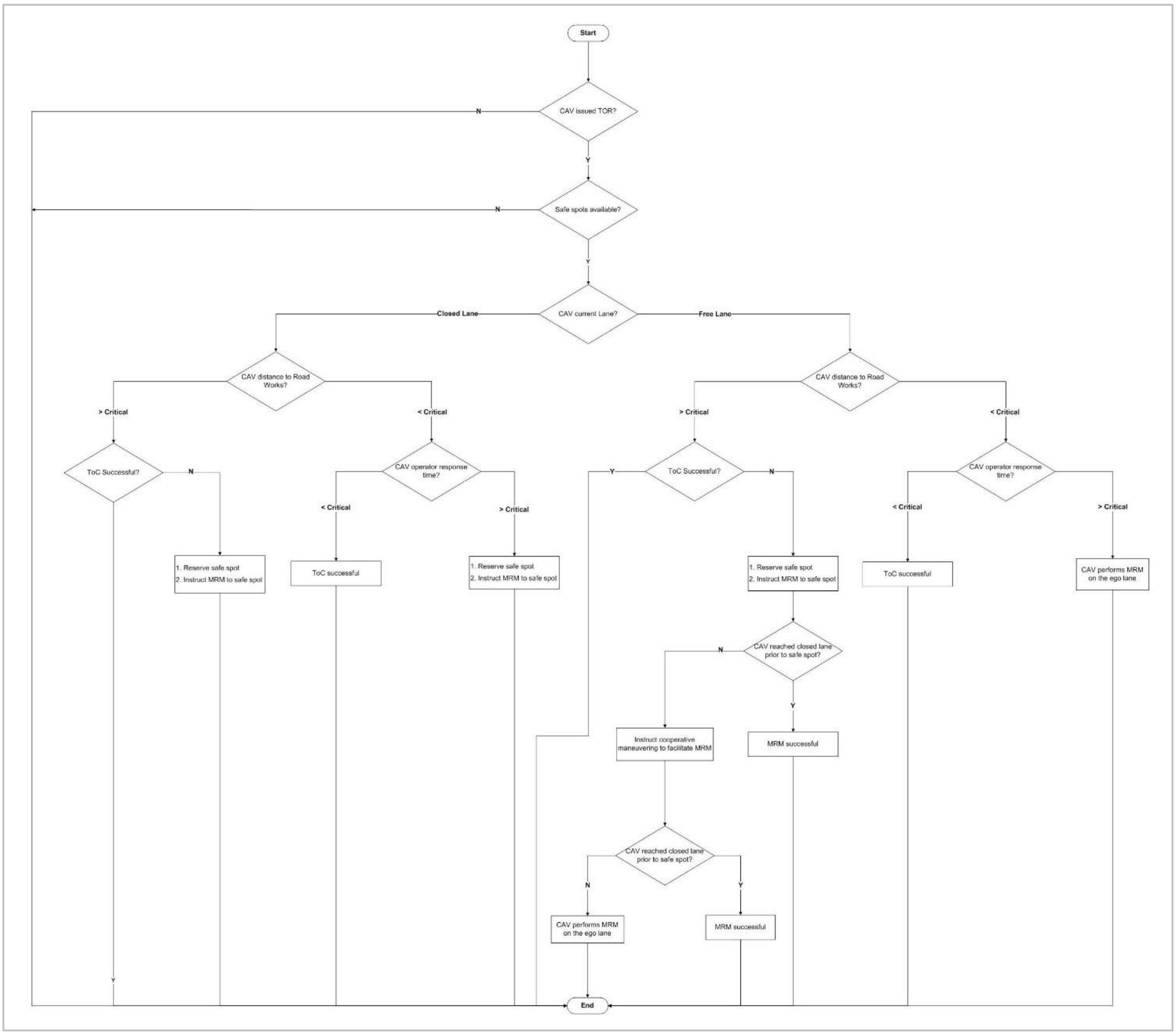


Figure 33: Control logic of the MRM management scheme.

3.1.4.2.3 CAV behaviour

If there is no available safe spot, the TMC provides no instructions to the CAV which performs an MRM in the current lane if necessary. On the other hand, if a safe spot is available, the TMC checks (a) if the CAV is driving in the closed or open lane, and (b) if its distance from the work zone is sufficient to accommodate the whole ToC duration and MRM when the ToC fails (critical distance). If the CAV is driving in the closed lane, and its distance from the work zone is larger than the critical distance, then the TMC will reserve the safe spot and guide the CAV accordingly in case the driver fails to resume vehicle control during the ToC. However, if the CAV distance from the work zone is less than the critical distance at the TOR onset, then there is no space available to accommodate the full ToC/MRM if required. Thus, the TMC needs to assess the driver's response time to the TOR. If the driver fails to take-over control within a critical time window ($criticalResponseTime = 6\ \text{s}$), that is narrower compared to the available lead time, then the TMC reserves a safe spot and instructs an early MRM to ensure that there is sufficient space for accommodating the MRM in a safe and timely manner (without excessive CAV braking). The aforementioned logic is also applied when the CAV is on the open lane at TOR issue. However, in this case the TMC provides additional lateral guidance to the CAV to reach the safe spot. Moreover, it can request cooperative manoeuvring from surrounding vehicles to facilitate the CAV lane change towards the safe spot.

The critical distance differs between the urban and the motorway case due to the different speed limits in the respective networks. The speed limit has been set $v_{\text{lim}}^{\text{urb}} = 13.89\ \text{m/s}$ for the urban case, and $v_{\text{lim}}^{\text{mot}} = 27.78\ \text{m/s}$ for the motorway case (upstream of the work zone). Since the time until the MRM was previously set $t_{\text{MRM}} = 10\ \text{s}$, then the Transition Area (TA) should stretch approximately $s_{\text{TA}}^{\text{urb}} = 140\ \text{m}$ for the urban network, and $s_{\text{TA}}^{\text{mot}} = 280\ \text{m}$ for the motorway network. The length of the MRM zone equals the CAV braking distance during the MRM, which is a function of the CAV travelling speed (speed limit for free-flow conditions) and the CAV braking capability during MRM ($a_{\text{MRM}} = 3.0\ \text{m/s}^2$). The MRM zone length is estimated using the equation elaborated in Section 2.2.2.2. Thus, in the urban network it spans approximately $s_{\text{MRM-Z}}^{\text{urb}} = 35\ \text{m}$, and in the motorway network $s_{\text{MRM-Z}}^{\text{urb}} = 130\ \text{m}$. Finally, the critical distance is determined to be $d_{\text{crit}}^{\text{urb}} = 200\ \text{m}$ for the urban scenario, and $d_{\text{crit}}^{\text{mot}} = 500\ \text{m}$ for the motorway scenario (see also Figure 34).

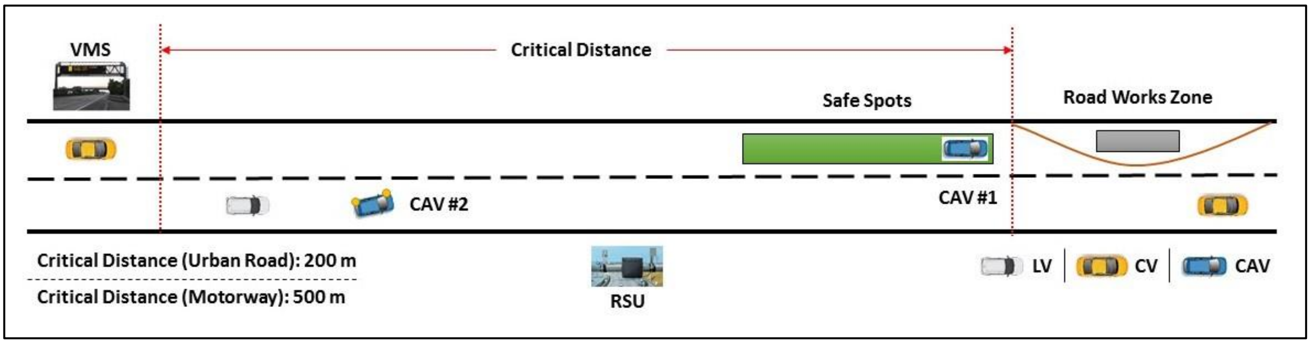


Figure 34: Critical distance upstream of the road works zone.

Note that in this deliverable the reservation and allocation mechanism of safe spots from the TMC is not examined. The same applies to cooperative manoeuvring which will be comprehensively investigated within WP3 activities, for which we refer to Deliverable D3.2.

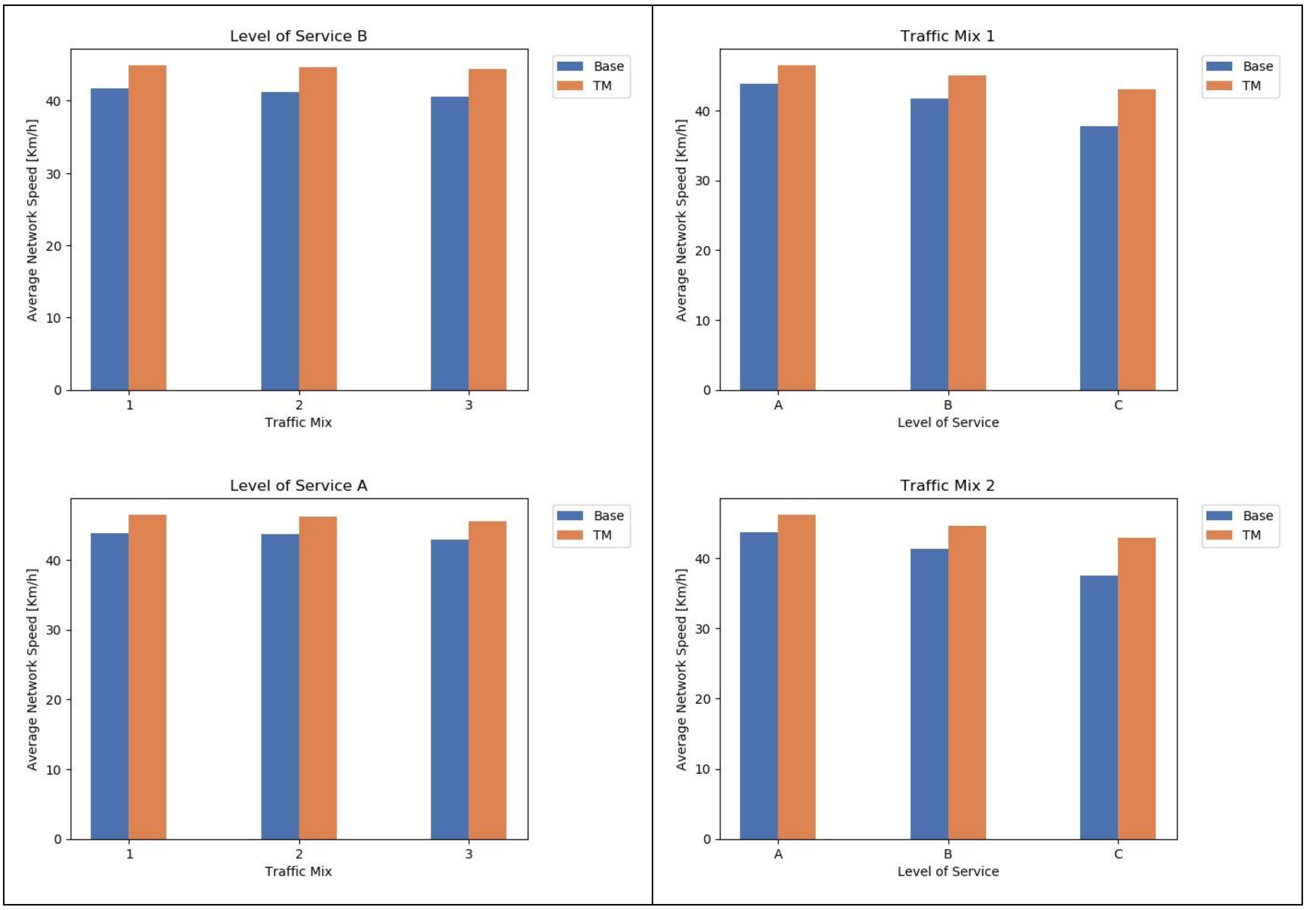
3.1.4.3 Results

3.1.4.3.1 Urban scenario

3.1.4.3.1.1 Impacts on traffic efficiency

Network-wide impacts

The average network speed for the examined vehicle mixes and traffic demand levels (LOS A to C) is depicted in bar plots, which represent both the baseline and the traffic management case (Service 4), and allow for a comparison between the two cases. The simulation results show that the implementation of Service 4 positively impacts all the tested scenarios in terms of network-wide traffic efficiency. However, the benefits become more pronounced for LOS C and vehicle mix 3, where Service 4 achieves 16% average network speed increase compared to the baseline (no control) case. Moreover, it can be observed that the network operates close to the speed limit (50 km/h) when traffic management is activated and traffic demand is low (LOS A and B). On the contrary, the average network speed varies around 40 km/h for the baseline conditions and low traffic demand (LOS A and B). Overall, traffic conditions improve significantly when Service 4 is applied to prevent MRMs leading to full vehicle stops occurring in the outer-most (open) lane.



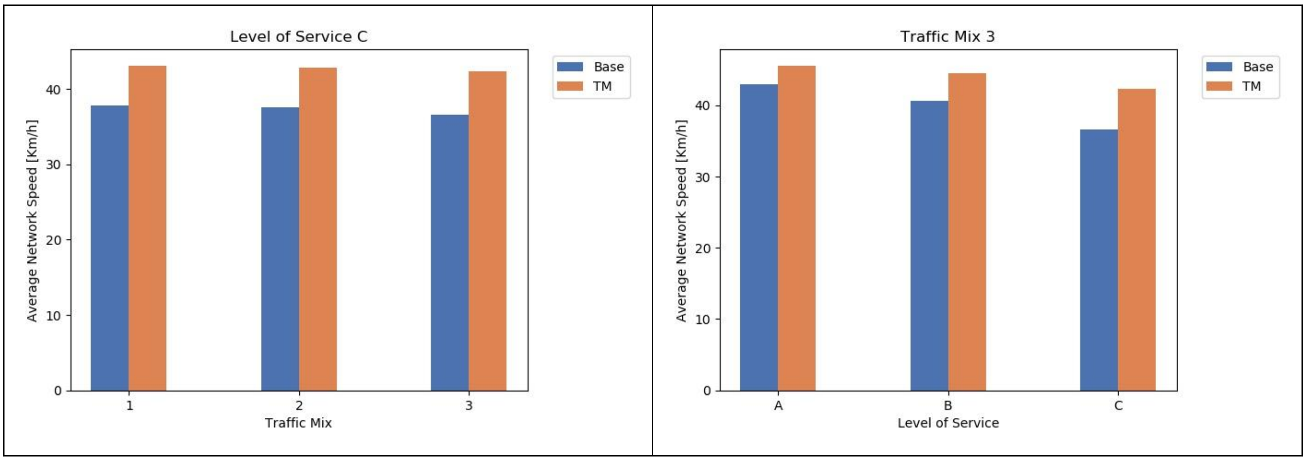
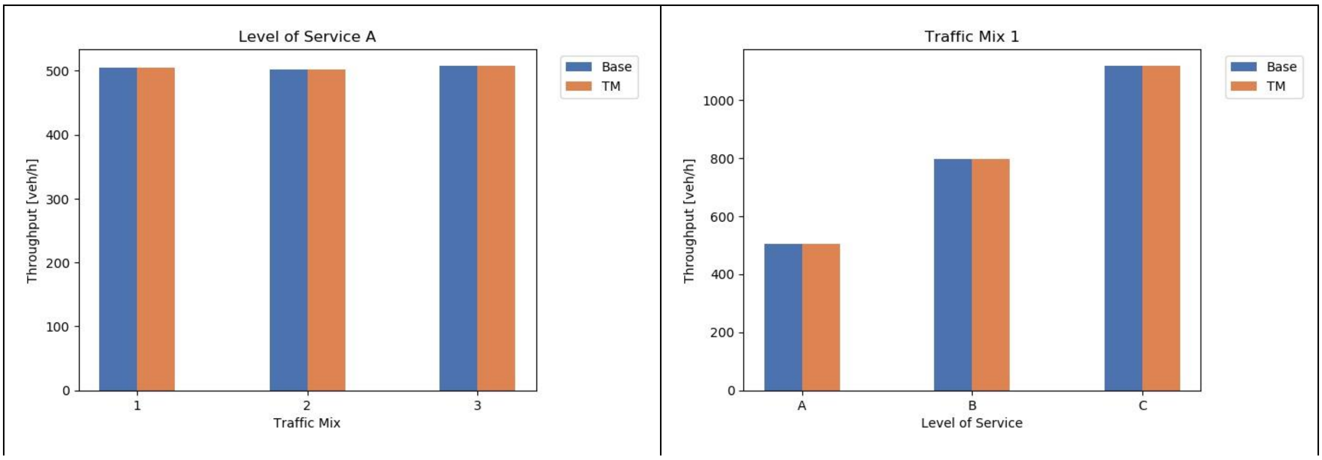


Figure 35: Average network speed for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Throughput remains unaffected by the implementation of Service 4. Figure 36 shows that throughput is almost identical between the baseline and the traffic management case for all tested scenarios (combinations of traffic demand levels and vehicle mixes). Moreover, the results indicate that the traffic demand input (per LOS) to the simulation network can be serviced during the simulation time horizon in any case (baseline or traffic management), since the reported throughput in the bar plots coincides with the input demand per LOS. This observation is reasonable considering the fact that the stopped CAV (after an MRM) only affects traffic operations for a delimited spatial and temporal horizon during the simulation timeline of the baseline scenarios as depicted in Figure 37.



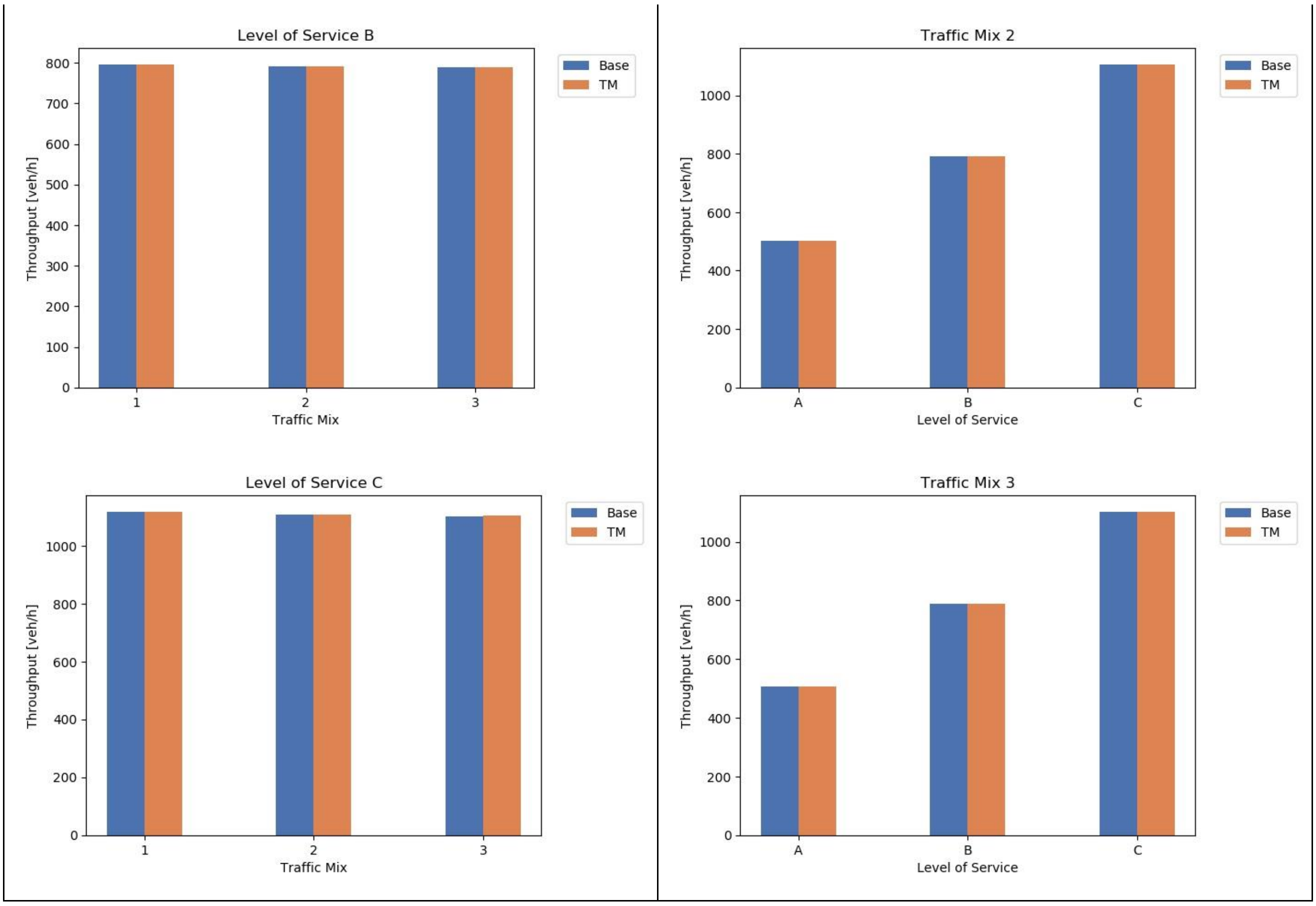


Figure 36: Throughput for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Local Impacts

The bar plots presented in the previous section, discussing the network-wide impacts of Service 4 in terms of traffic efficiency, indicated that the average network speed increases when traffic management is applied, while throughput remains unchanged compared to the baseline case. The latter results are also justified by the speed and flow tempo-spatial diagrams created based on detector data and shown in Figure 37 (example diagrams for LOS C, vehicle mix 2, seed 0).

We observed the CAV stopping after an MRM blocks the outer lane at time $t_{\mathrm{stop}} = 9$ min and location $x_{\mathrm{stop}} = 0.9$ km, and thus congestion propagates upstream until the network entrance. The vehicle remains stopped for $d_{\mathrm{rt}} = 5$ min ($driverResponseTime = 300$ s), and then at time $t_{\mathrm{to}} = 16$ min congestion starts to dissolve since the CAV operator has regained vehicle control and cleared the blocked lane (upper left plot of Figure 37). Traffic flow drops accordingly to zero downstream of the lane drop while the CAV remains stopped, and then spikes while the upstream queue is dissipating after the CAV operator takes over vehicle control (lower left plot of Figure 37).

On the other hand, no significant speed variations are observed in the traffic management case (upper right plot of Figure 37), since the TMC guides the CAV to the safe spot and the outer lane remains open. Thus, no spillback occurs and the traffic flow remains stable throughout the simulation timeline (lower right plot of Figure 37). Moreover, it can be seen that the tempo-spatial diagrams of flows are almost similar during the second half of the simulation duration between the baseline and the traffic management cases, since the effects of the previously stopped CAV (after an

MRM) have dissolved. Thus, the hourly throughput between the two cases is similar as previously shown in the bar plots.

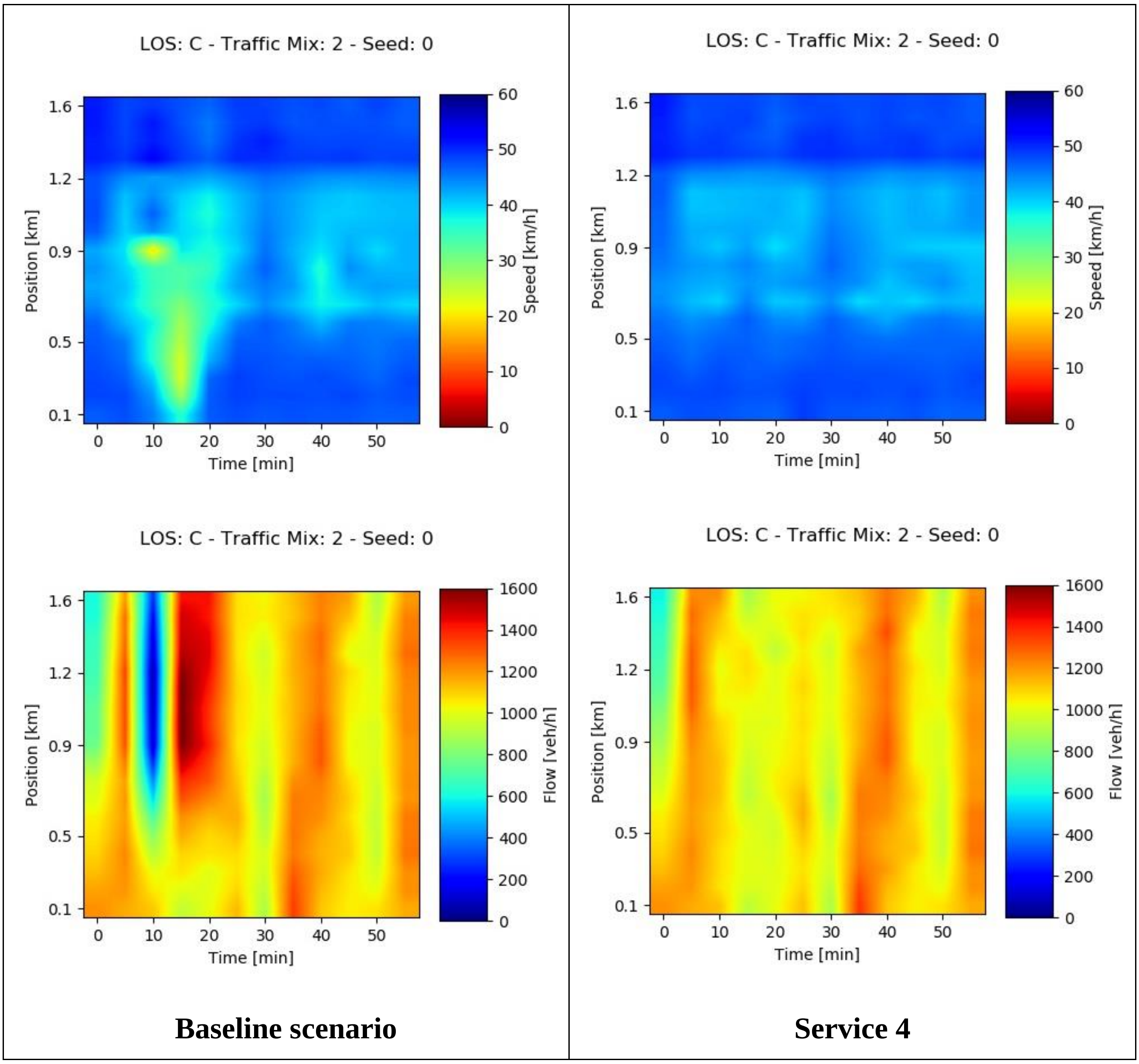


Figure 37: Example speeds and flows tempo-spatial diagrams for use case 4.2 (LOS C, vehicle mix 2, urban network). The left column corresponds to the baseline scenario and the right column to the traffic management (Service 4) scenario.

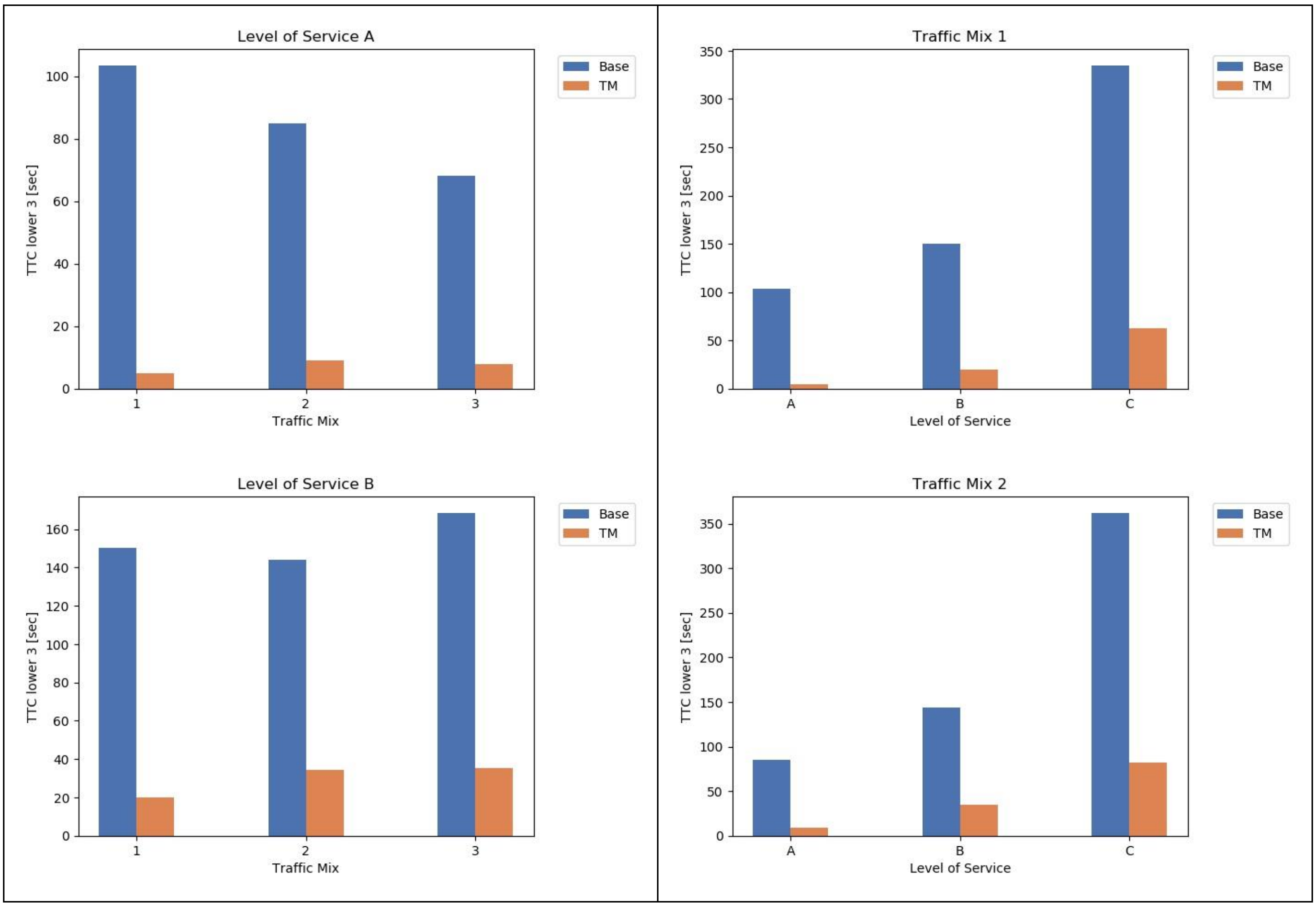
3.1.4.3.1.2 Impacts on traffic safety

Figure 38 shows the average number of safety-critical events occurring for the examined simulation scenarios (traffic demand levels, vehicle mixes, traffic management case). Safety-critical events are assessed based on the TTC indicator within the context of this research. Vehicle interactions encompassing TTC less than 3 seconds for a vehicle are considered as safety critical.

The traffic safety results depicted in the bar plots indicate that Service 4 yields significant safety benefits compared to the baseline case irrespective of the traffic demand level and vehicle mix. These benefits become substantially profound for vehicle mix 1 when the share of LVs is higher. We observe that for LOS A and vehicle mix 1 the reduction in safety-critical events rises to 90%. This phenomenon can be attributed to the lane change behaviour of C(A)Vs which are more conservative compared to the LVs. Thus, as they approach the work zone, they require larger gaps to merge into the open lane. When these gaps are not available, the C(A)Vs might have to brake sharply behind the CAV that has been already guided to the safe spot. Hence, when traffic demand increases (LOS B to C) and the share of C(A)Vs also increases, the number of safety-critical events increases as well. This behaviour was previously encountered and explained in the simulation experiments conducted within Deliverable D3.1 for the same use case.

On the other hand, no clear pattern can be observed with respect to the safety-critical events of the baseline scenarios. For LOS A the number of safety-critical events is monotonically decreasing with increasing C(A)V share, while for the other LOS there is no visible trend. The observed results regarding LOS A follow from the fact that the CAV stops next to the closed lane after an MRM since it is unaffected by the surrounding vehicles. Therefore, approaching LVs change lane to the closed one to gain an advantage compared to those vehicles already queued in the previously open lane. The higher aggressiveness of LVs in the terms of gaining advantage results in more erratic and safety-critical behaviour. However, for LOS B and C the CAV stopping after an MRM can be affected by nearby vehicles prior to the MRM, and thus not necessarily stop next to the work zone. In this case there is room for surrounding vehicles to overtake the stopped CAV and continue their trip. Then, the number of safety-critical events depends on the location of the stopped vehicle (after an MRM) upstream of the work zone and the behaviour of the overtaking vehicles. Thus, the picture regarding traffic safety becomes mixed and unpredictable.

Finally, the simulation results also indicate that increasing traffic flow and density (from LOS A to LOS C) generates more safety-critical events due to more intense vehicle interactions. This observation can be made both for the baseline and the traffic management case.



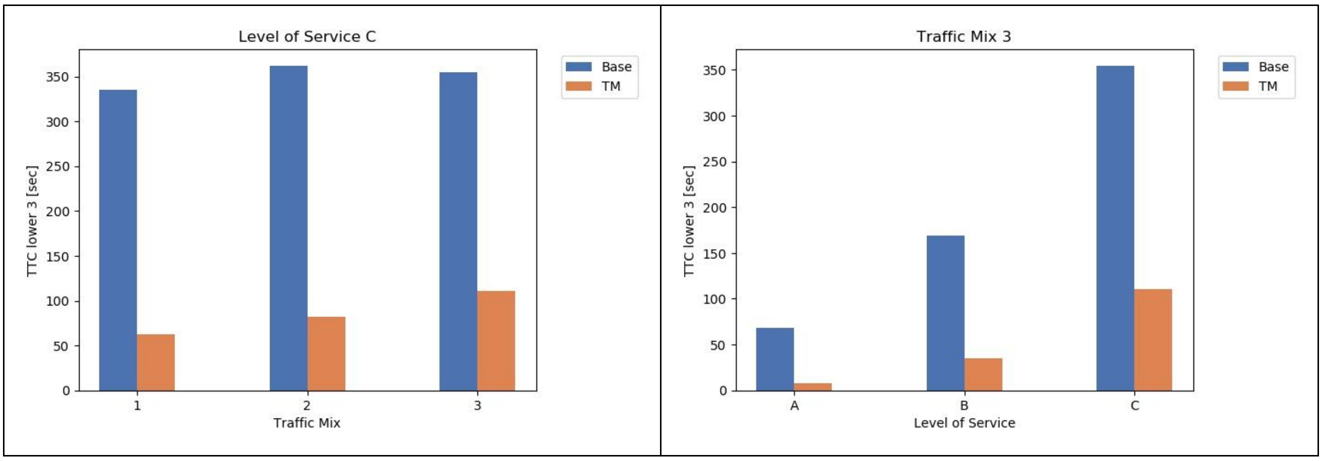
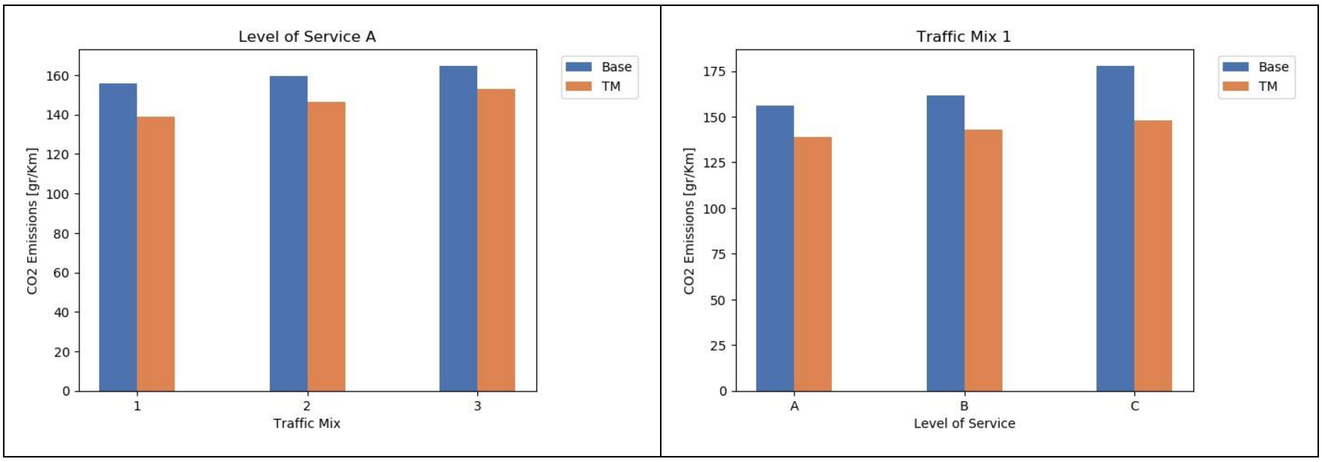


Figure 38: Average number of safety-critical events (TTC < 3.0 s) for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mix). Different bar colours correspond to baseline and traffic management simulations.

3.1.4.3.1.3 Environmental impacts

The environmental impacts of Service 4 on the urban network are assessed in terms of CO_2 emissions per kilometre travelled for the different traffic demand levels and vehicle mixes. CO_2 emissions are significantly lower for the traffic management case irrespective of the LOS and the vehicle mix (see also Figure 39). The environmental benefits become the highest for LOS C, and especially vehicle mix 3, when Service 4 achieves CO_2 emissions reduction of approximately 18%. In general, CO_2 emissions results are in accordance with the traffic efficiency results presented earlier. The implementation of Service 4 ensures that traffic operates near the speed limit (50 km/h, average network speed plots) and that speed oscillations due to the stopped CAV close to the work zone, are prevented (tempo-spatial plots of speed). Thus, CO_2 emissions do not significantly increase for higher LOS when Service 4 is implemented.



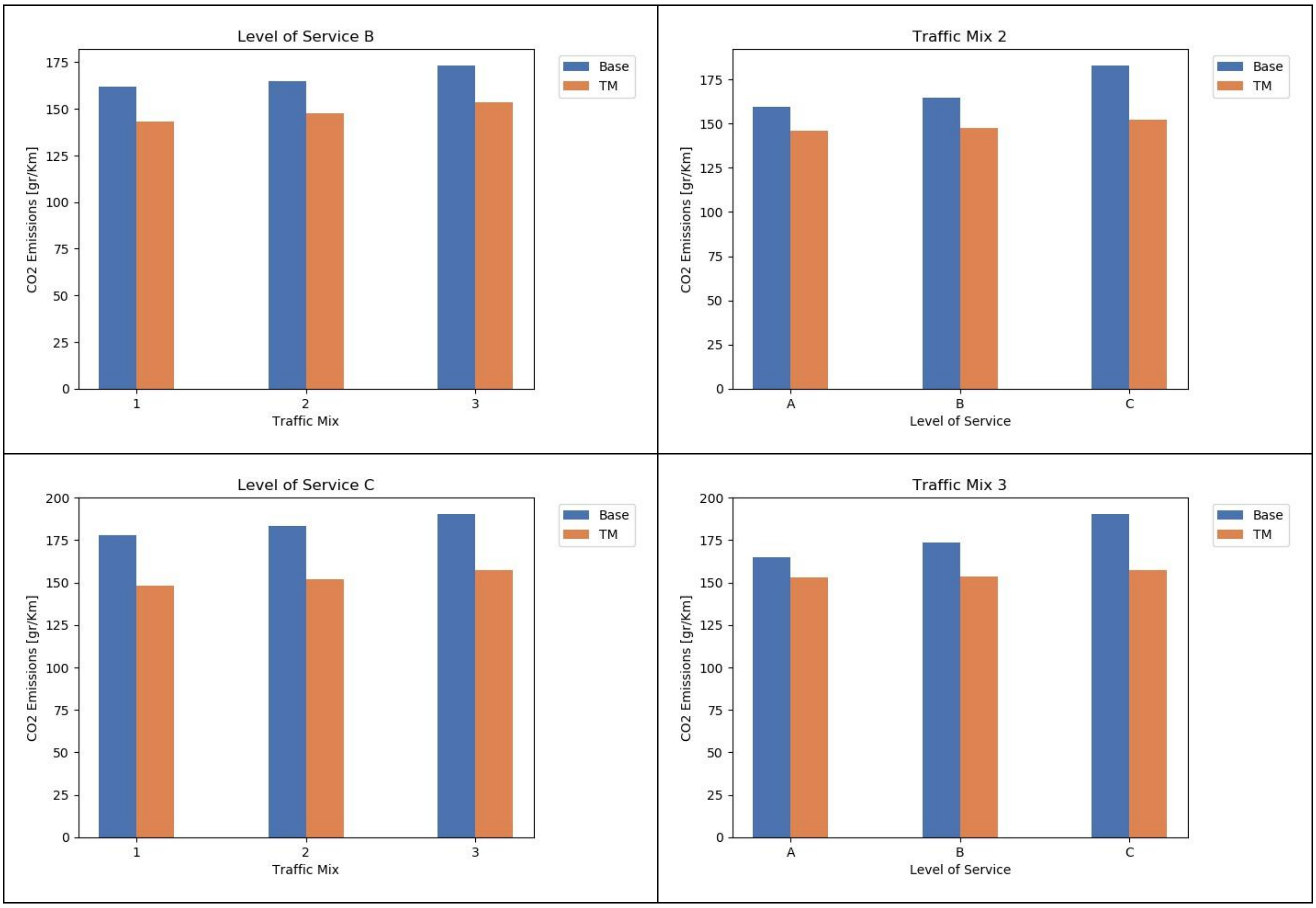


Figure 39: Average CO_2 emissions per kilometre travelled for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

3.1.4.3.2 Motorway scenario

3.1.4.3.2.1 Impacts on traffic efficiency

Network-wide impacts

The bar plots in Figure 40 show that the implementation of Service 4 improves traffic efficiency on the motorway network for all the examined scenarios encompassing alternative traffic demand levels and vehicle mixes. The improvement in terms of average network speed ranges between 10% and 15% for LOS A and B, irrespective of the vehicle mix. Higher variability in the observed traffic efficiency benefits occurs for a higher demand level (LOS C) due to congestion. Finally, simulation results show that traffic efficiency diminishes in the presence of more C(A)Vs both for the baseline and the traffic management case. This finding stems from the more conservative C(A)V behaviour (car-following, lane changing, and gap acceptance) compared to LVs and coincides with previous results presented in Deliverable D3.1.

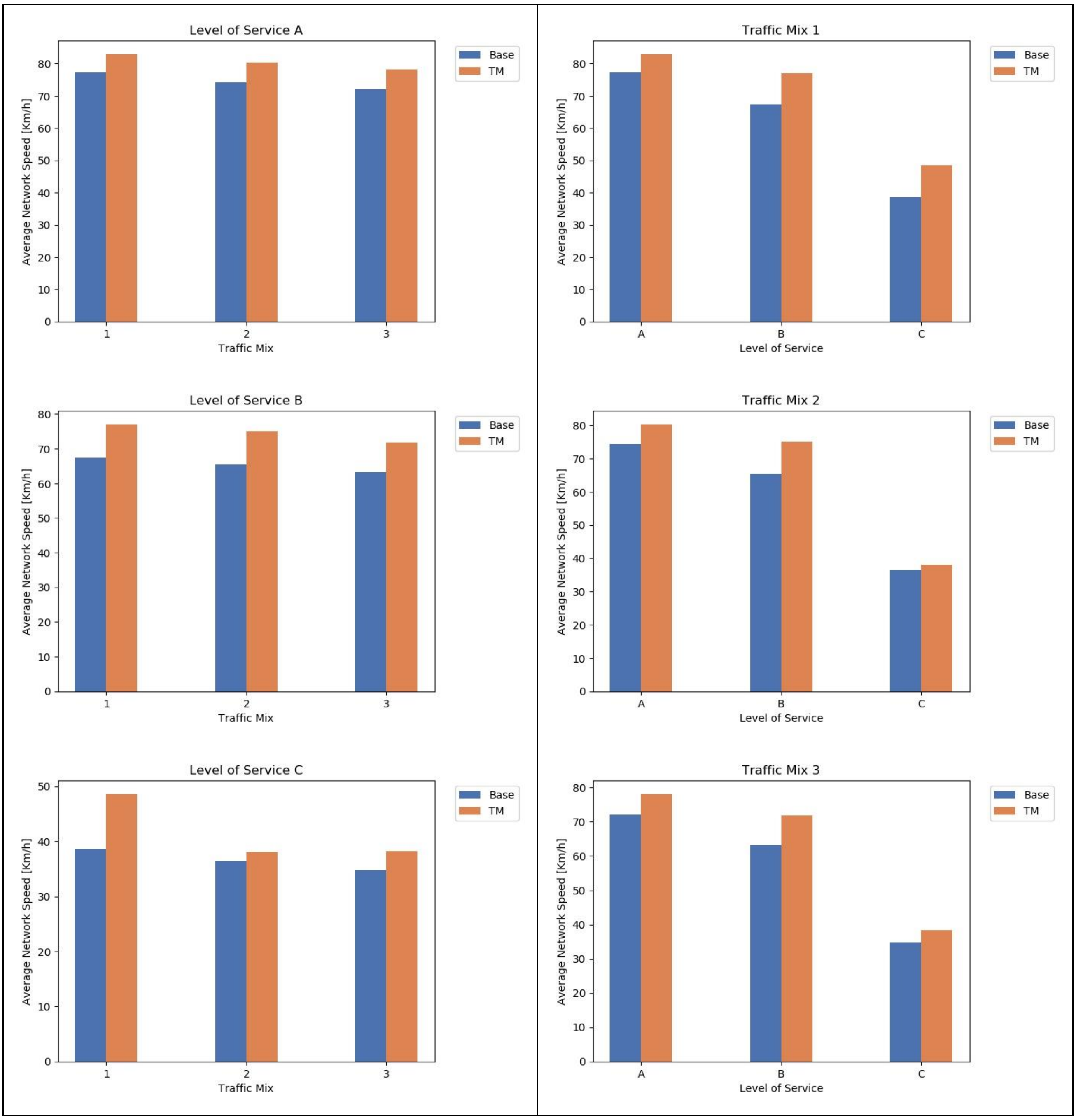


Figure 40: Average network speed for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Throughput is similar between the baseline and the traffic management case in the motorway scenario as well. As described before, the stopped CAV (after an MRM) affects the baseline scenario only for a delimited tempo-spatial window, and thus traffic demand can be accommodated within the whole simulation timeline but at the expense of traffic efficiency. According to the simulation results depicted in Figure 41, throughput coincides with the induced traffic demand in the motorway simulation network for LOS A and LOS B irrespective of the vehicle mix. On the contrary, throughput is lower compared to the induced demand for LOS C due to congestion. Moreover, results show that the vehicle mix is not an influential factor with respect to throughput.

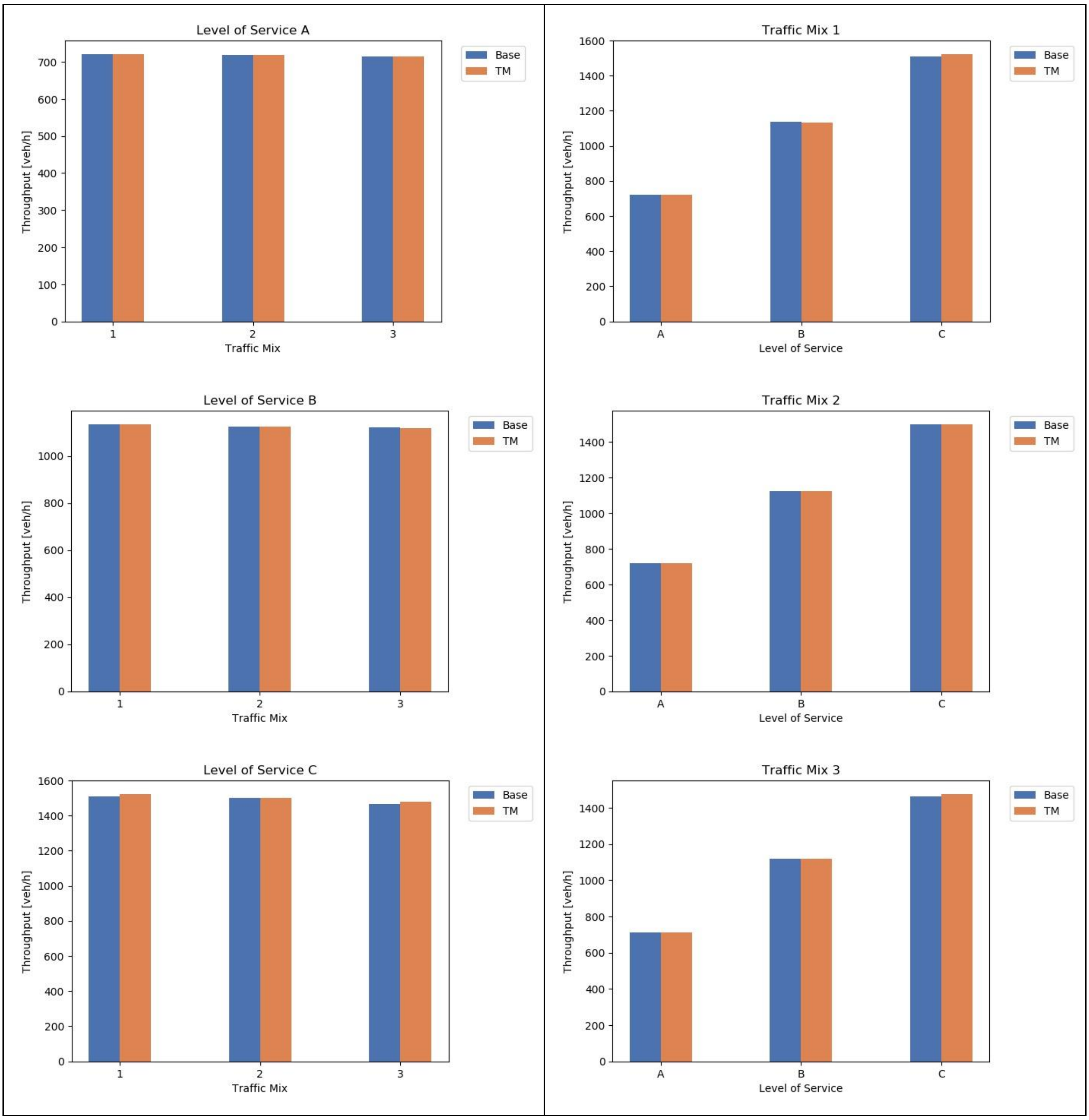


Figure 41: Throughput for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and vehicle simulations.

Local Impacts

The local impacts in terms of traffic efficiency of the unmanaged MRMs on the motorway network are shown in Figure 42 (upper and lower left diagrams). The CAV stops (after an MRM) near the work zone causing spillback to propagate upstream for approximately 500 m (upper left plot of Figure 42). When the CAV operator regains vehicle control, the spillback gradually dissipates until it is fully resolved. On the contrary, when the CAV is guided to the safe spot by the TMC, the breakdown is prevented and the observed speed reduction results explicitly from the work zone (upper right plot of Figure 42). As in the urban scenario, traffic flow spikes downstream of the lane drop while the queued vehicles dissipate (lower left plot of Figure 42). During the second half of the simulation duration, the flow pattern between the baseline and the traffic management case is the same, thus justifying the same performance between the two cases with respect to throughput. Finally, we note that the presented results in Figure 42 correspond to LOS B and vehicle mix 2, but are typical for all scenarios encompassing uncongested conditions (LOS A and B and vehicle mixes 1 to 3). However, the observed traffic pattern is different for LOC C due to increased congestion which provides limited space for improvement to Service 4.

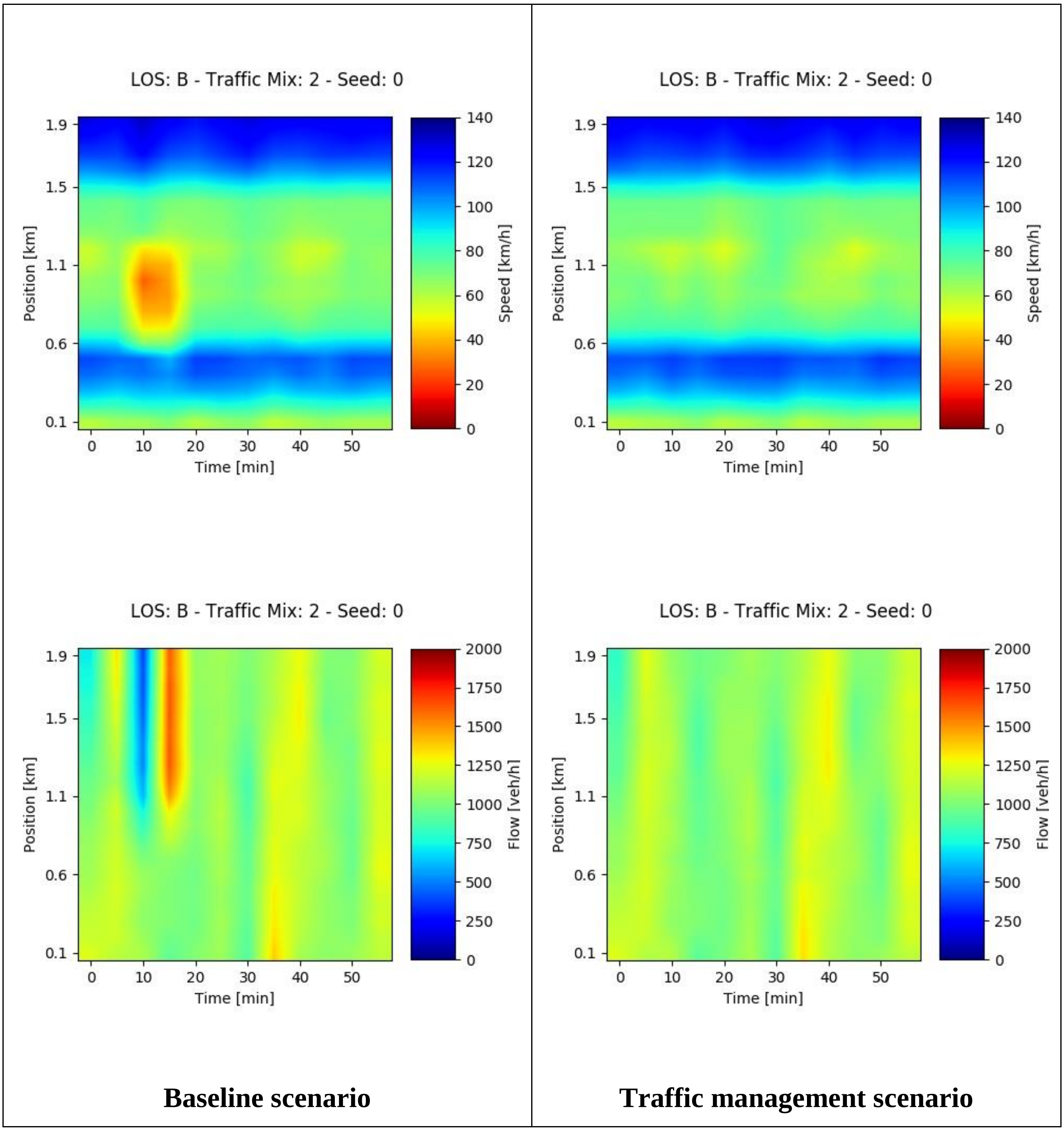


Figure 42: Example speed and flow tempo-spatial diagrams for use case 4.2 (LOS C, vehicle mix 2, motorway network). The left column corresponds to the baseline scenario and the right column to the traffic management (Service 4) scenario.

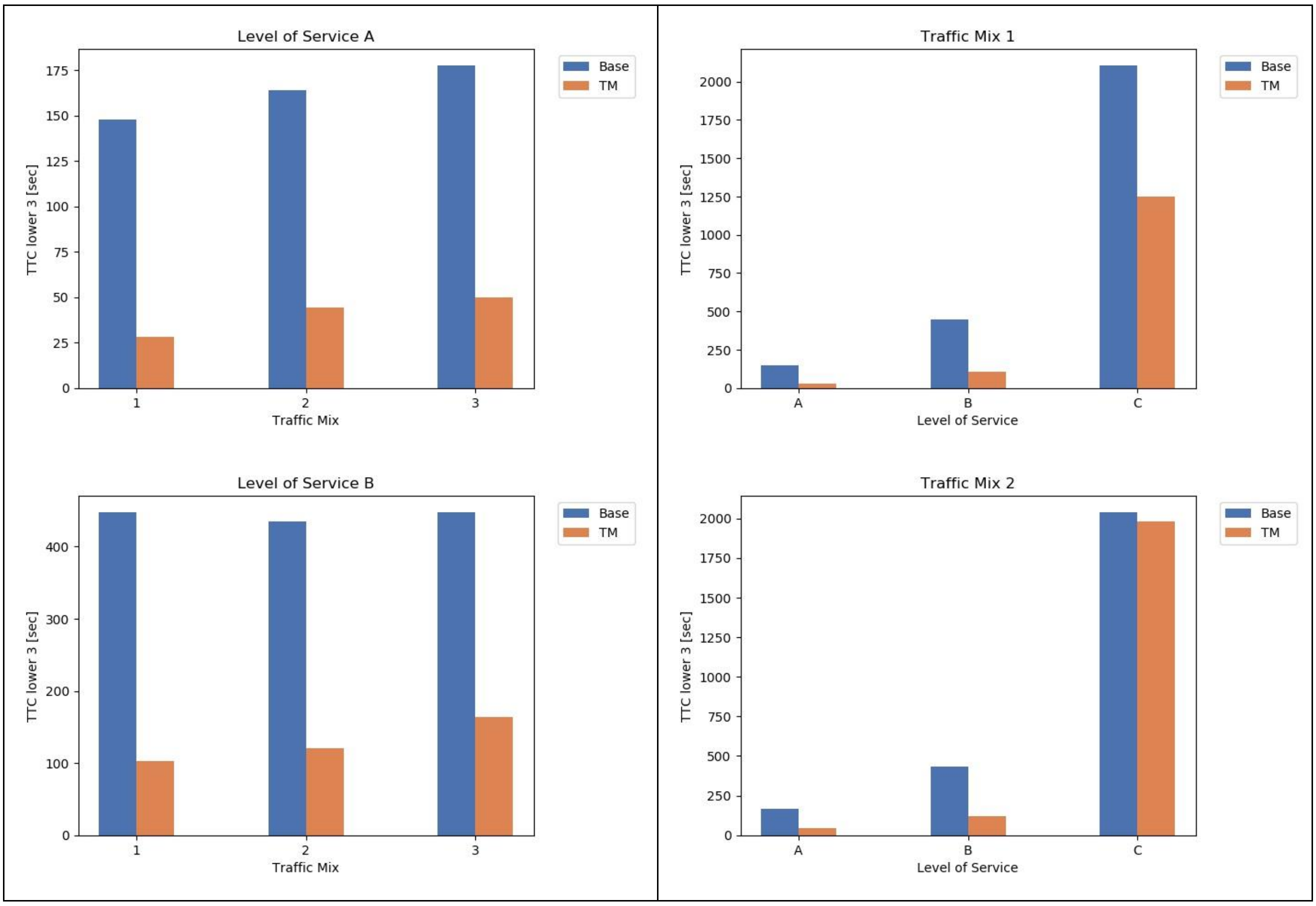
3.1.4.3.2.2 Impacts on traffic safety

Service 4 yields significant safety benefits for the motorway scenario too. These benefits are particularly significant for low traffic demand (LOS A and B), when the number of safety-critical events can be decreased up to 85% (LOS A and vehicle mix 1). As it was observed in the urban scenario, safety-critical events monotonically increase with the increasing share of C(A)Vs for the traffic management case due to the more conservative C(A)V lane change behaviour compared to manual driving. However, this trend only prevails for uncongested traffic conditions (LOS A and B).

On the contrary, we now observe in Figure 43 that for LOS A safety-critical events increase monotonically with the increased share of C(A)Vs. This finding contradicts the results observed in the urban scenario, where the opposite trend prevailed. However, since LOS A corresponds to a higher flow rate on the motorway case, this phenomenon can be attributed to the surrounding traffic preventing the CAV from stopping next to the work zone after an MRM, but eventually rather upstream. Thus, overtaking activity from surrounding vehicles influences safety in a non-deterministic way, even for low traffic conditions in the motorway scenario.

Safety benefits minimise when traffic conditions become congested (LOS C). In this case, the increased traffic flow results in long queues upstream of the lane drop which render traffic management infeasible. The TMC cannot guide the CAV to the safe spot since queued vehicles waiting to merge into the open lane next to the work zone occupy it.

Finally, the simulation results indicate that increasing traffic flow and density (from LOS A to LOS C) generate more safety-critical events due to more intense vehicle interactions for the motorway scenario as well.



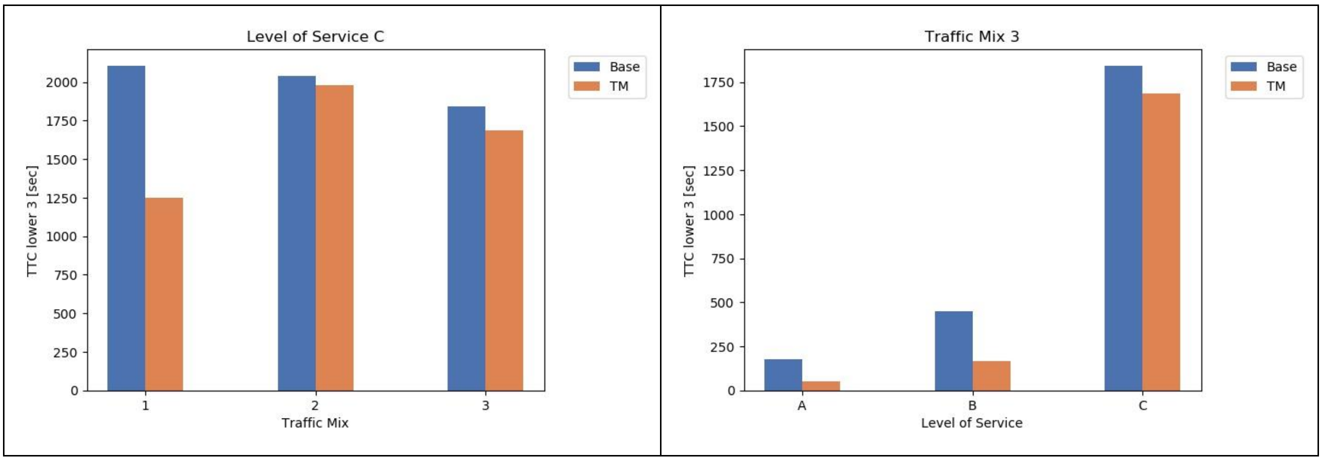


Figure 43: Average number of safety-critical events (TTC < 3.0 s) for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

3.1.4.3.2.3 Environmental impacts

The MRM guidance to the safe spot results in CO_2 emissions reduction for all the examined scenarios (traffic demand levels and vehicle mixes). The reduction becomes higher when the motorway network is not heavily congested (LOS A and B) ranging between 5% to 10% for the different vehicle mixes. Moreover, CO_2 emissions increase with increasing share of C(A)Vs since traffic efficiency deteriorates due to the more conservative car-following and lane change behaviour of C(A)Vs compared to LVs. Additionally, increased congestion produces excessive CO_2 emissions. Overall, CO_2 emissions benefits presented in Figure 44 are in accordance with the aforementioned traffic efficiency impacts (network-wide and local) of Service 4.

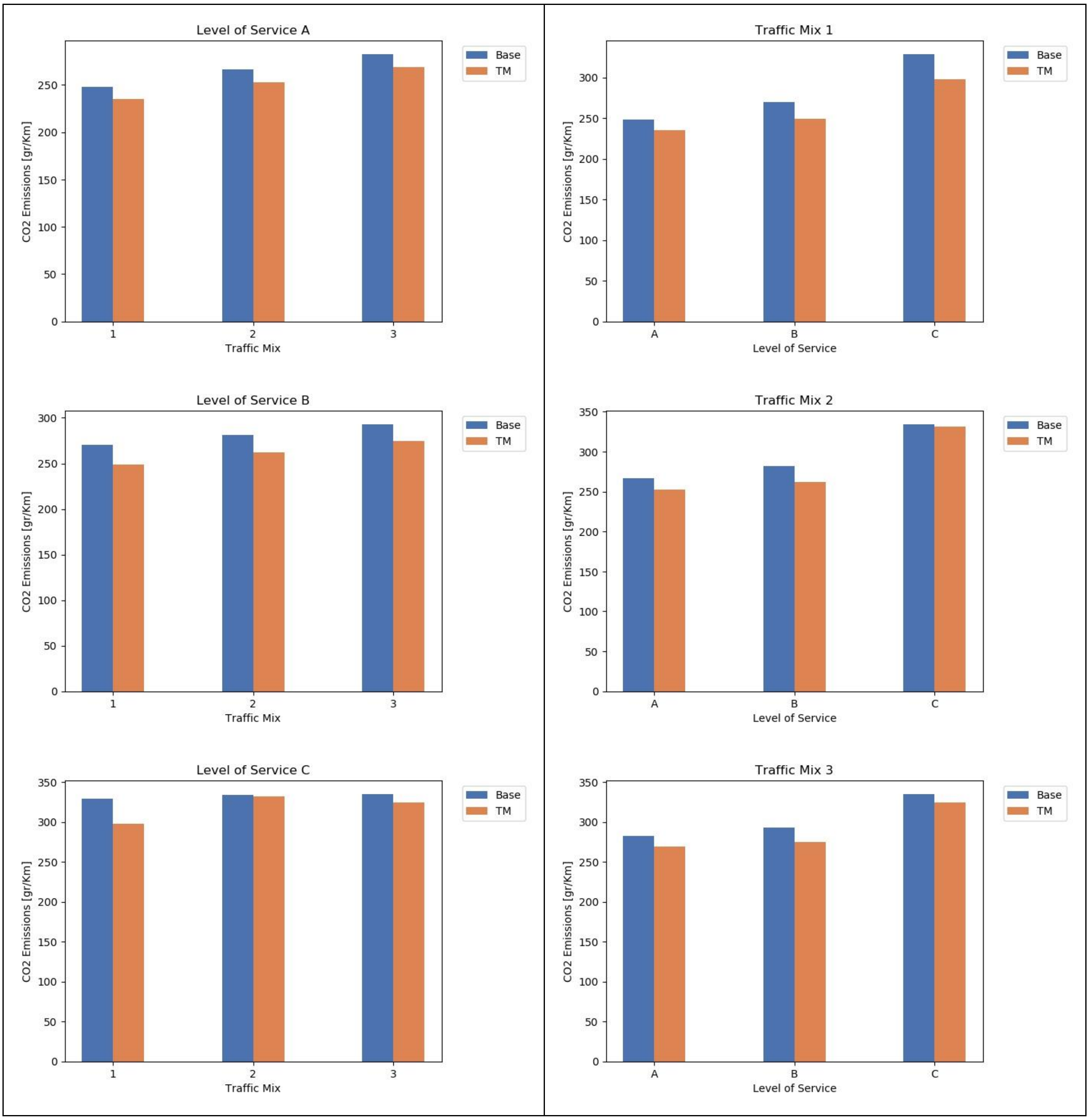


Figure 44: Average CO_2 emissions per kilometre travelled for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

3.1.4.4 Discussion

The guidance of a CAV performing an MRM to a safe spot upstream of road works was demonstrated to provide significant benefits in terms of traffic safety, efficiency, and emissions reduction. Simulation results indicated that the benefits are more profound when prevailing traffic conditions are uncongested and networks operate in free-flow conditions. In particular, we found that the traffic flow disturbance induced by the CAV stopping in the open lane upstream of the work zone can be prevented, thus leading to increased network performance in terms of average network speed. Since the CAV remains stopped only for a confined time interval, network throughput remains unaffected. Moreover, we verified that CAVs operating explicitly under ACC demonstrate a reduced performance in terms of traffic efficiency as identified in Deliverable D3.1.

Traffic safety is affected by the stop location of the CAV after an MRM during the baseline simulation experiments. If the CAV stops upstream of the work zone and other vehicles can overtake it to pass through the work zone, then traffic safety can be further undermined. However, if the CAV reaches the safe spot with the TMC guidance, then safety-critical events are significantly reduced. This occurs explicitly when safe spots are free and not occupied but queued vehicles attempting to merge into the open lane by the work zone. Thus the benefit of the service diminishes in case of severe congestion upstream of the work zone. Finally, Service 4 also results in CO_2 emissions savings for all tested traffic demand levels and vehicle mixes both for the urban and the motorway scenario. These savings maximise for low traffic conditions when the Service prevents CAV from closing the available free lane.

3.1.5 Service 5 (use case 5.1): Distribute ToC/MRM by scheduling ToCs

3.1.5.1 Introduction

As elaborated in Deliverable D2.2, external reasons might determine if automated driving will be forbidden in certain traffic areas (which we call ‘no automated driving’ (NAD) zones). Service 5 aims to inform approaching C(A)Vs in order to initiate transitions to manual driving in a coordinated manner. In absence of additional guidance and coordination we expected to have an accumulated occurrence of transitions at specific locations, which can lead to adverse effects regarding traffic safety and efficiency. Thus, Service 5 implements a scheme for the distribution of TORs sent to C(A)Vs ahead of the NAD zone within a dedicated TOR area (as shown in Figure 45).

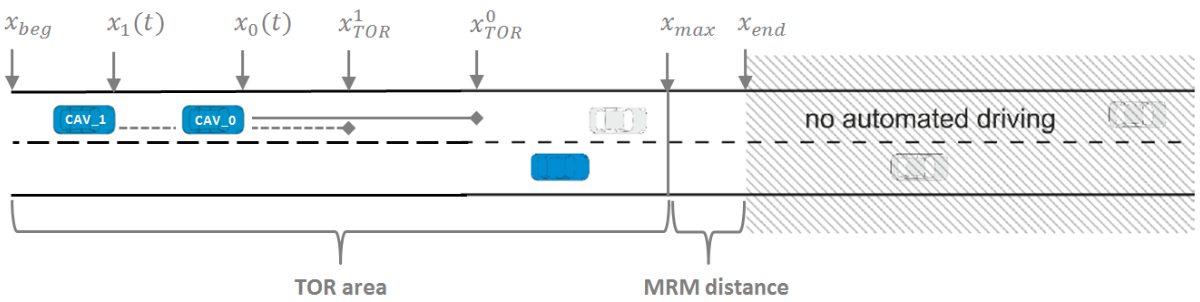


Figure 45: Schematic distribution area for TORs within a transition area.

3.1.5.2 Traffic management setup

In Figure 46 the principle control logic of Service 5 is presented as a flow chart. The TMC monitors the area upstream of the NAD zone and regularly obtains positions and speeds from each C(A)V. Furthermore, information about the traffic distribution in the monitored area is derived from collective perception and road side detectors.

Consecutive C(A)Vs are pooled into groups at the entrance to the monitored area, and their transitions are supervised and coordinated algorithmically. The traffic management algorithm assigns a TOR schedule for every vehicle depending on the estimated density within the TOR area, the current position, and speed of the vehicle, and its position within the corresponding vehicle group.

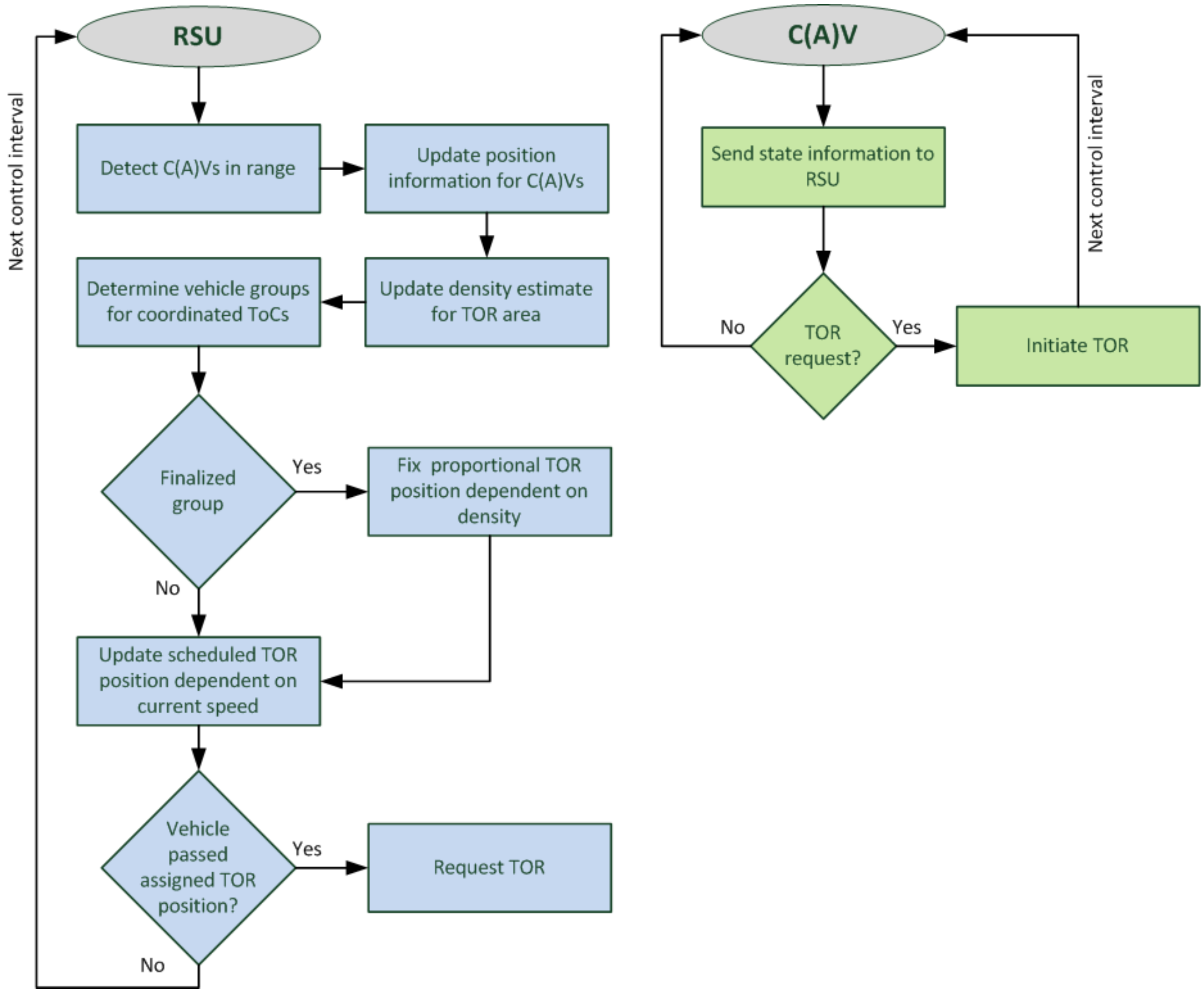


Figure 46: Traffic management service for use case 5.1.

3.1.5.2.1 TOR scheduling algorithm

In-group coordination

To schedule the TORs for vehicles within a group, the time interval D_t between successive TORs is calculated as a first step. It defines the timelapse between requests sent out to the group's vehicles starting with the vehicle located at the trailing position and proceeding vehicle by vehicle until all members of the group have received a TOR. This successive procedure aims at preventing the compounding of braking efforts. Such a phenomenon occurs if all vehicles of a group would simultaneously establish an increased gap prior to the transition and potentially leads to unnecessarily low speeds (see Figure 47).

The exact value of D_t is determined heuristically by the assumption of a definite value g_1 for the spacing targeted prior to the actual takeover. The maximal potential difference between the headway prior to the TOR and the target spacing is:

$$D_\mathrm{g} = g_1 - g_\mathrm{A} \tag{3}$$

where g_A is the assumed minimal accepted headway during automated driving. As a general form for g_1 we consider:

$$g_1 = SPACING_{\mathrm{TOR}} + TIMEGAP_{\mathrm{TOR}} * v(t) \quad (4)$$

where $v(t)$ is the vehicle's current speed and the quantities $SPACING_{\mathrm{TOR}}$ and $TIMEGAP_{\mathrm{TOR}}$ are parameters of the algorithm, see Table 12 further on. Similarly, the minimal time headway during automated driving can be as small as:

$$g_{\mathrm{A}} = SPACING_{\mathrm{A}} + TIMEGAP_{\mathrm{A}} * v(t) \quad (5)$$

Thus, the estimated maximal increase of the gap is:

$$D_{\mathrm{g}} = g_1 - g_{\mathrm{A}} = \frac{{D_{\mathrm{t}}}^2}{2b} \quad (6)$$

Assuming a constant brake rate $b = B_{\mathrm{GAP}}$ we choose:

$$D_{\mathrm{t}} = \sqrt{2 * D_{\mathrm{g}} * b} \quad (7)$$

as the estimated maximal time required to achieve the desired spacing g_1. Given an appropriate parametrisation, this choice should prevent accumulated braking efforts.

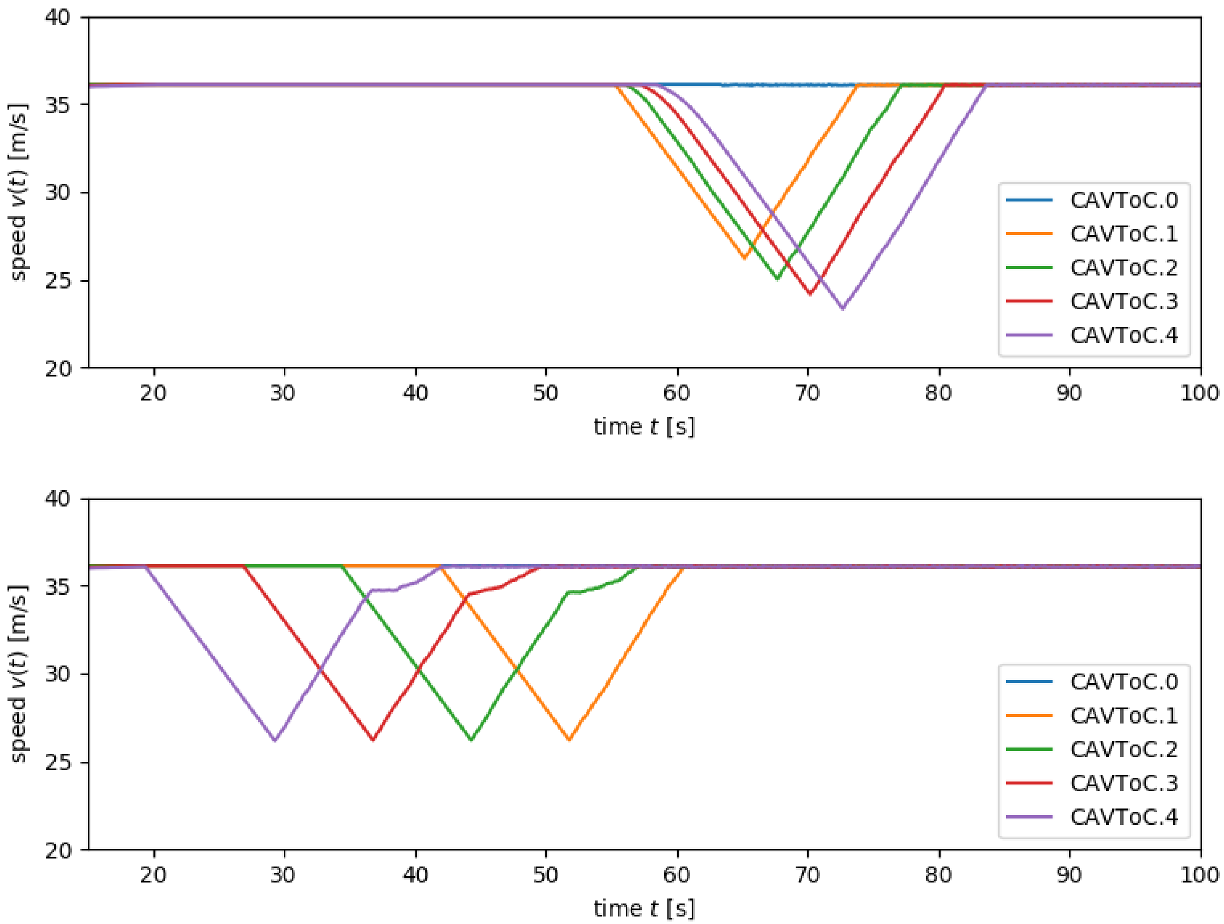


Figure 47: Speed runplots for different TOR scheduling approaches for a group of five CAVs. Upper panel: simultaneous TORs as frequently occurring in baseline case. Here issued at $t \approx$

55 s; Lower panel: distributed TORs starting with a TOR for the trailing vehicle with ID 'CAVToC.4' at $t \approx 20$ s. If TORs are issued simultaneously, the minimal observed speed is approximately 23 m/s, while in the distributed case it only drops to approximately 26 m/s during the preparation phase for the ToC.

Density dependent choice of TOR positions

After D_t is determined, the positional TOR-coefficients for the group's members are calculated in dependence of the downstream density. For N members, the scheduled TOR times for the vehicles are given as:

$$t_i = t_0 - i * D_t \tag{8}$$

where t_0 is the TOR time of the leader and D_t are the intervals between TORs given to successive platoon members. Let v_0 be the current speed of the leading vehicle, then the value of t_0 is determined as its estimated arrival time with $t_0 = \max\left\{0, \left(x^0_{\mathrm{TOR}} - x_0(t)\right)/v_0\right\}$ at a point x^0_{TOR} between $x_{\max}$, the point at the closest admissible distance to the NAD zone for a TOR, and the entry point to the TOR area x_{beg}. The exact location x^0_{TOR} scales linearly between these extremes in proportion to the renormalised downstream density $\rho(t)$:

$$x^0_{\mathrm{TOR}} = \min\{x_{\max}, x_{\mathrm{beg}} + \rho(x_{\max} - x_{\mathrm{beg}})\} \tag{9}$$

Here we use $\rho = occ(t)/MAX\_OCCUPANCY$, where $occ(t)$ is the current occupancy of the monitored area in percentage and $MAX\_OCCUPANCY$ is a parameter (see Table 12). For $\rho = 1$, the leader's TOR is issued immediately, i.e. $x_{\mathrm{TOR}} = x_{\mathrm{beg}}$, for $\rho = 0$, it is scheduled for $x^0_{\mathrm{TOR}} = x_{\max}$. Given t_i, from (8) we obtain corresponding TOR-points:

$$x^i_{TOR} = x_i + t_i * v_0 \tag{10}$$

with the current position x_i of the i-th vehicle.

Dynamic scaling of chosen TOR positions

We define the TOR coefficients as proportions of distance to the scheduled TOR points x^i_{TOR}:

$$\theta_i = \frac{x^i_{\mathrm{TOR}} - x_i}{x_{\max} - x_i} \tag{11}$$

That is:

$$x^i_{\mathrm{TOR}} = x_i + \theta_i * (x_{\max} - x_i) \tag{12}$$

which is used to update the value of x^i_{TOR} according to the current value of $x_{\max}$ in consecutive control intervals.

Parameters for the traffic management procedure and their values adopted in the presented simulations are summarised in Table 12.

Table 12: Parameters for the TOR scheduling algorithm.

Parameter	**Default value**	**Description**
MAX_PLATOON_SPACING	20 m	Parameter for platoon management: spacing (threshold for accepting new vehicles in group)
MAX_PLATOON_TIMEGAP	3.5 s	Parameter for platoon management: time gap (threshold for accepting new vehicles in group) (Spacing and time gap operate conjunctively: if one encompasses the candidate vehicle, it can be added)
PLATOON_CLOSING_DIST	120 m	Distance beyond the ToC zone entry, at which an entering platoon will be closed the latest
PLATOON_CLOSING_TIME	5 s	Closing time is the maximal time after which a platoon is closed if no further vehicles are added
MRM_DECEL	3.0 s	Assumed (minimal) deceleration rate applied during MRM
OPENGAP_BRAKE_RATE	1.0 m/s^2	Assumed maximal brake rate applied during opening a gap in the preparation phase for a takeover
$\mathrm{SPACING}_{\mathrm{TOR}}$	10 m	Assumed minimal spacing to be obtained by the open gap mechanism
$\mathrm{TIMEGAP}_{\mathrm{TOR}}$	2.0 s	Assumed minimal time headway to be obtained by the open gap mechanism
$\mathrm{TIMEGAP}_{\mathrm{A}}$	1.5 s	Assumed minimal time gap used by the automated car-following controller
$\mathrm{SPACING}_{\mathrm{A}}$	0 m	Assumed minimal spacing used by the automated car-following controller
MAX_OCCUPANCY	10%	Value for the lane occupancy at which TORs should be issued immediately at vehicle detection

3.1.5.2.2 C(A)V behaviour

An important addition to the CAV models that were used in the baseline simulations (see Deliverable D3.1) is the introduction of a preparatory action prior to the actual ToC. As soon as a C(A)V receives a TOR, it prepares a safe transition by increasing its headway to the vehicle in front in order to leave more time and space for the manual driver to react accordingly to the take-over situation. We assume that this manoeuvre is executed with a moderate maximal braking rate of 1 m/s^2. After this preparation the ToC is performed and the vehicle continues driving in manual mode. Here we expect the vehicle to catch up closer to the vehicle in front, now accepting smaller headways than C(A)Vs do (for details on the model parameters see Deliverable D3.1).

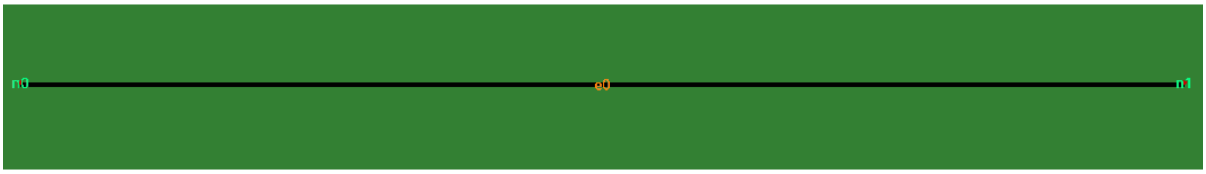
3.1.5.2.3 Baseline scenario adaptation

This traffic management mechanism may be accompanied by a slowdown of a C(A)V during the preparation phase and may imply speed reductions of following vehicles. If such manoeuvres are discarded without further coordination and concentrated at a specific location, this may result in an accumulation of deceleration efforts within a group of C(A)Vs. Depending on the traffic density and the share of CAVs, this may represent an important factor impairing a smooth traffic flow. The baseline simulations in Deliverable D3.1 did not reflect this model aspect, which is why updated simulations were chosen for a comparison of the scenarios in presence and absence of traffic management measures for Service 5. Although the fine tuning of parameters for the preparation phase is an open task, the qualitative picture of the results reported here is expected to persist for different parametrisations as long as the preparation headway is to some extent larger than the usually accepted headway during automated operation.

For purposes of information retrieval, we placed detectors on each lane of the road section close to the merge area. The detected vehicle data will be used to decide if the open-gap function should be applied. All simulation settings for Service 5 are recapitulated in the tables in the Appendix in Section 5, as well as the overview in Table 13 with the relevant changes highlighted in yellow. For each scenario (LOS and vehicle mix combination) 10 runs with different random seeds are executed.

Table 13: Adapted network configuration details for use case 5.1. Adaptations in yellow.

Scenario 5.1	Settings	Notes
Road section length	5.0 km	
Road priority	3	
Allowed road speed	36,11 m/s	• 130 km/h
Number of nodes	2	• n0 – n1
Number of edges	1	
Number of O-D relations	1	• n0 to n1
Number of lanes	2	• 2 normal lanes
Work zone location	-	
Closed edges	-	
NAD_ZONE_ENTRY_POS	2500 m	Entry position of the NAD zone on single edge
Disallowed vehicle classes	• normal lanes: pedestrians, tram, rail_urban, rail, rail_electric, ship	• from n0 to n1
Filenames	• network: TransAID_UC5-1.net.xml	
Intended control of lane usage CAVs and other traffic are approaching a NAD zone with 2 lanes. Starting about 2.5 km upstream from the		

NAD zone, the TMC determines through collective perception the positions and speeds of vehicles and determines the optimal location and moment for CAVs to perform a downward ToC. Subsequently, ToC requests are provided to the corresponding CAVs. Based on the ToC requests, the CAVs perform ToCs at the desired location and moment in time and transition to manual mode. CVs are warned about the ToCs and possible MRMs. In the NAD zone, the CAVs are in manual mode.
Network layout 
Road segments n0→n1: (5.000 m)

3.1.5.3 Results

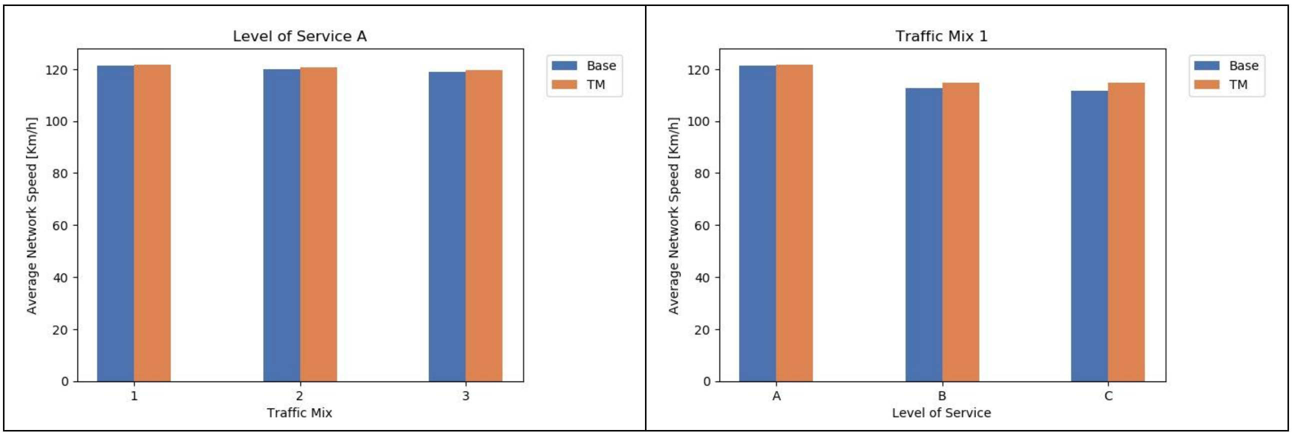
3.1.5.3.1 Impacts on traffic efficiency

Network-wide Impacts

Figure 48 shows the average network speed for the different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and traffic management Service 5.

We observe that in the baseline, the average speed is decreasing with a higher LOS and an increased share of automated vehicles. This contrasts the results of Deliverable D3.1 where no difference could be observed due to a simplified modelling of the ToC preparation phase. The loss of efficiency up to almost 60% is severe for LOS B and C with a vehicle mix of 2 and 3 (the average speed drops to around 50km/h).

In presence of TransAID traffic management the average speed loss is marginal across all LOS and vehicle mix variants. In particular it is always higher than in the baseline runs, with a significant difference for LOS B and C with increased shares of C(A)Vs.



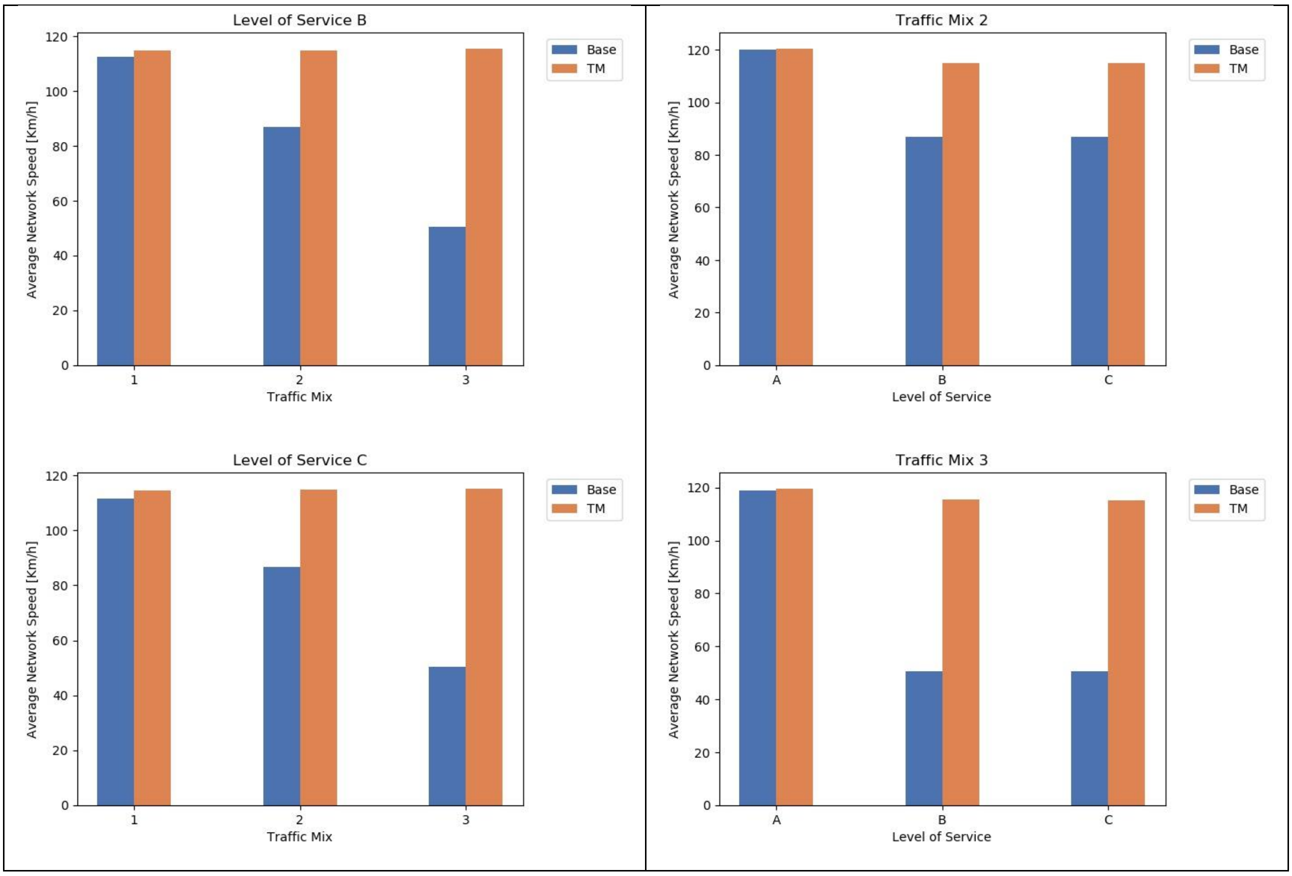
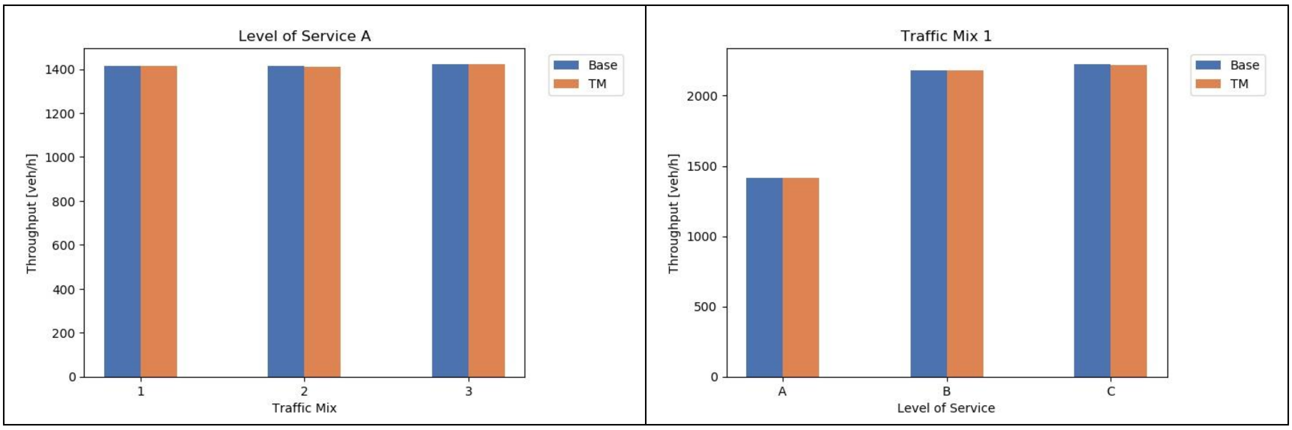


Figure 48: Average network speed for use case 5.1 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Figure 48 shows the throughput for use case 5.1 for different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and traffic management service (note that the scaling of the throughput is not equal for every chart).

For both baseline and traffic management simulations, the throughput increases with higher LOS and decreases with CAV shares. Notably the throughput is significantly higher in presence of the traffic management Service 5 than for the baseline with approximately plus 250-300 vehicles per hour in case of vehicle mix 3, LOS B and C, indicating that this scenario yields the highest benefits for the service in terms of traffic efficiency.



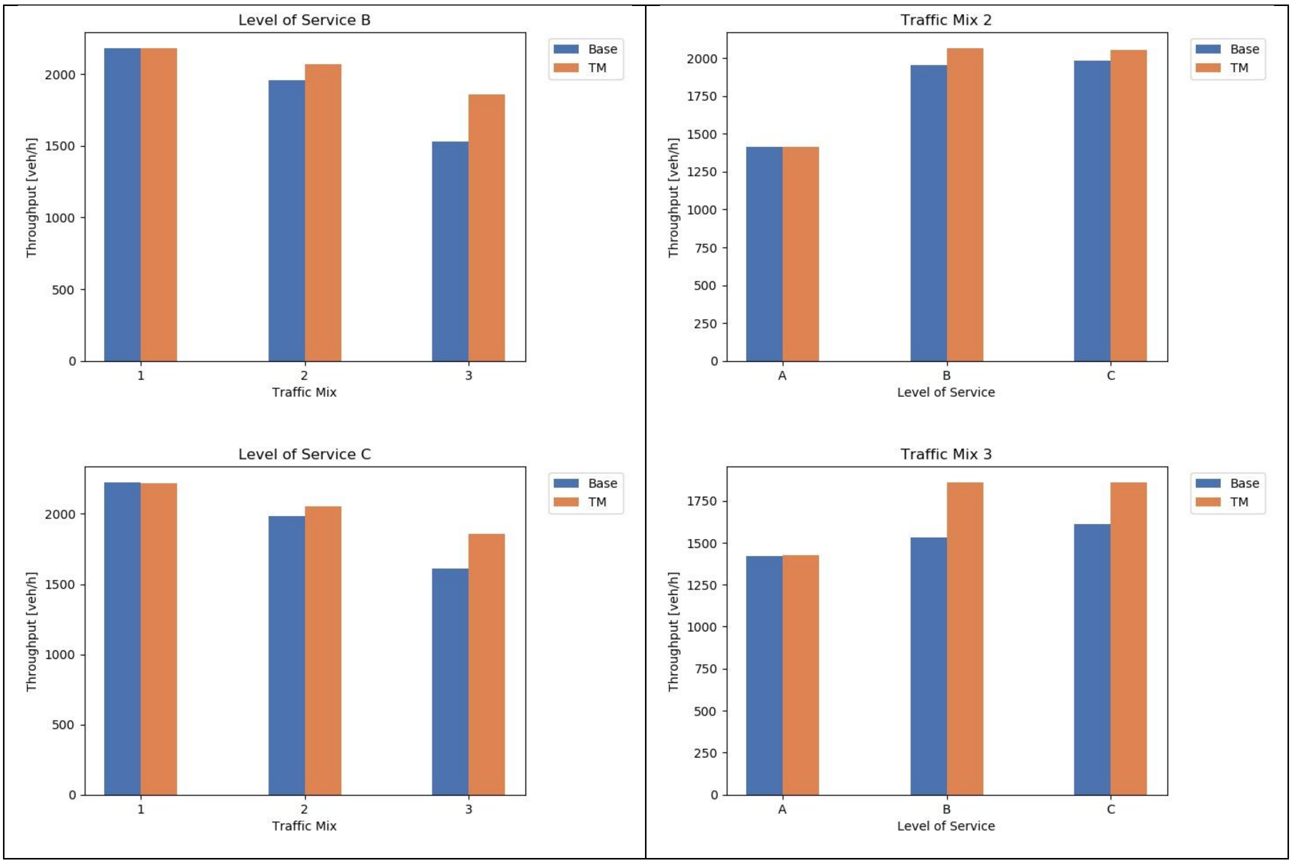


Figure 49: Throughput for use case 5.1 (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Local Impacts

Figure 49 illustrates the speed losses and reduced flows for the sample of LOS C, vehicle mix 3, seed 6. The NAD zone starts at a position of 2.5 km. For the baseline we observe a breakdown of average speed triggered by perturbances arising from several simultaneous ToCs at close locations. Such disruptions leading to a stationary bottleneck located at the NAD zone entry occur in most simulations runs sooner or later within the one hour simulation interval. Once developed, the bottleneck hardly dissolves if demand is not low (LOS B and C). In the depicted example the bottleneck emerges already after approximately five minutes and congestion rapidly grows filling the simulated area after approximately 25 minutes (cf. the red area in the upper left plot of Figure 50).

These phenomena vanish in the presence of a coordinated distribution of TORs. Even if local disruptions are present (i.e. the lighter spots in upper left plot of Figure 50), the prevention of locally concentrated series of ToCs allows them to dissolve such that a smooth flow is re-established (cf. the green-yellow areas in lower right plot of Figure 50).

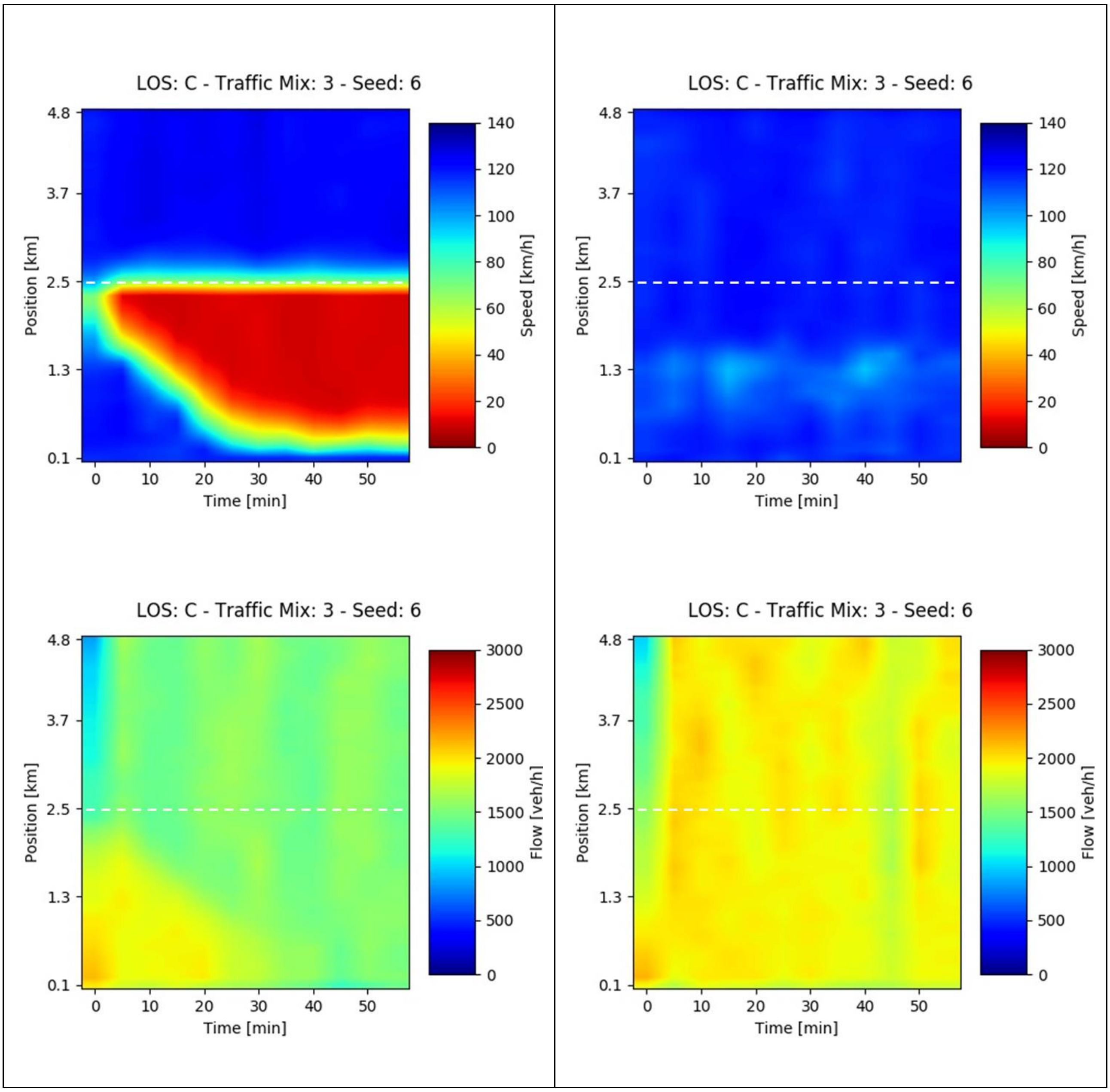


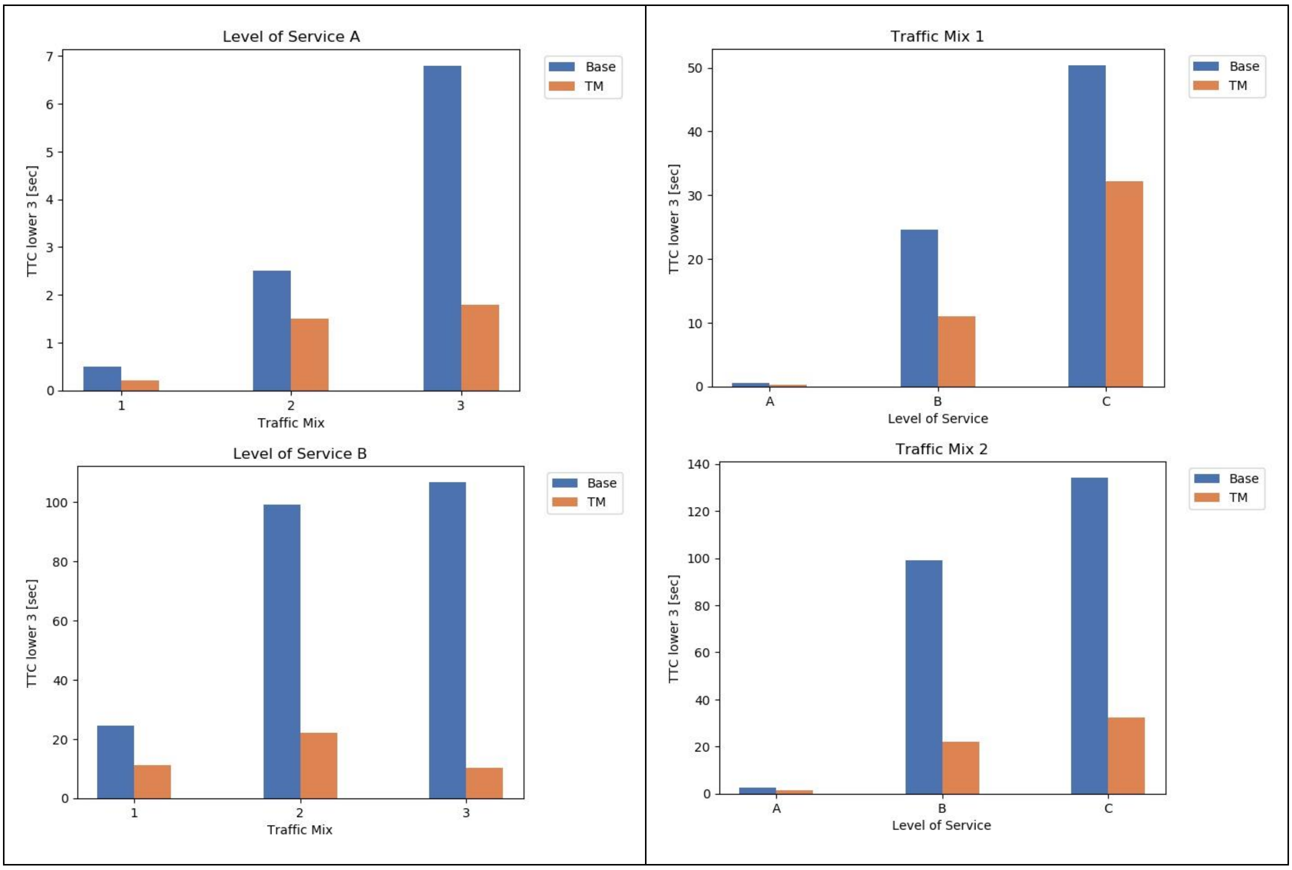
Figure 50: Example tempo-spatial diagrams for measured speeds (upper row) and flows (bottom row) for use case 5.1 (LOS C, vehicle mix 3, seed 6). The left column corresponds to the baseline and the right column to the applied traffic management Service 5 simulations. The white dashed line marks the entry position of the NAD zone.

3.1.5.3.2 Impacts on traffic safety

Figure 51 shows the number of critical events with a TTC lower than 3.0 seconds for the different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and traffic management service (note that the scaling of the number of critical TTCs is not equal for every chart).

For the baseline we observe a monotonic increase in the number of critical events for higher LOS and vehicle mixes, most pronounced for LOS B and C with vehicle mixes 2 and 3, which indicates relatively few vehicle interactions for other scenarios. This contrasts previous results obtained from a simplified modelling of the ToC preparation phase (see Deliverable D3.1) where no difference could be observed.

If traffic management Service 5 is in operation, the number of critical TTC events drops significantly in all scenarios when compared to the baseline. It increases as traffic demand changes from LOS A to C. However, in contrast to the baseline results, the observed dependence of critical events per hour on CAV shares is non-monotonic with a maximum for an intermediate proportion of CAVs. The reason for this non-monotonicity may be that the interactions between CAVs and LVs, which occur at highest rates for homogeneous mixes, are the most problematic. However, this issue is to be examined more carefully in the future as it can be expected to be even more pronounced when considering critical events per kilometre driven.



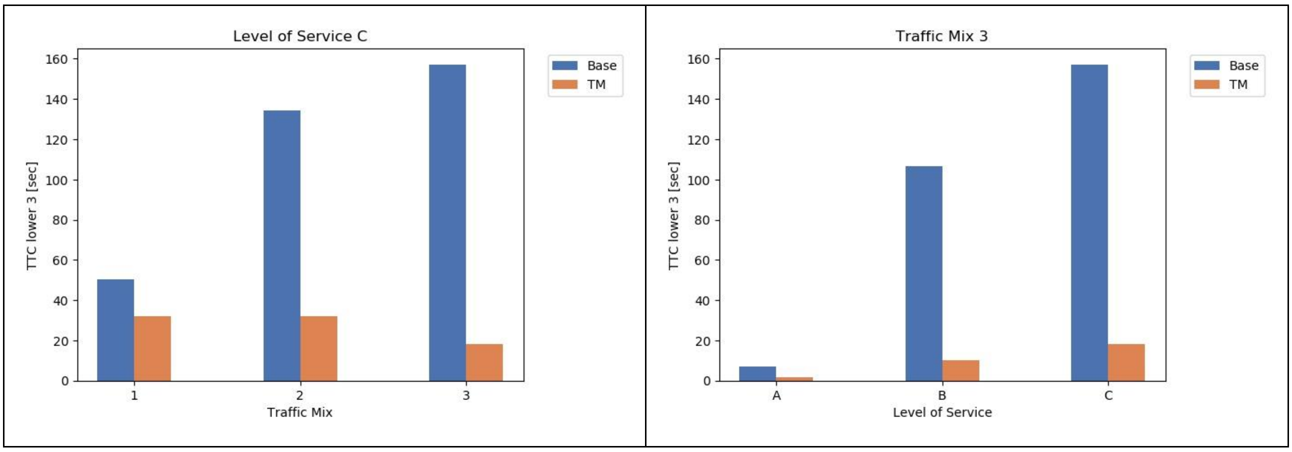
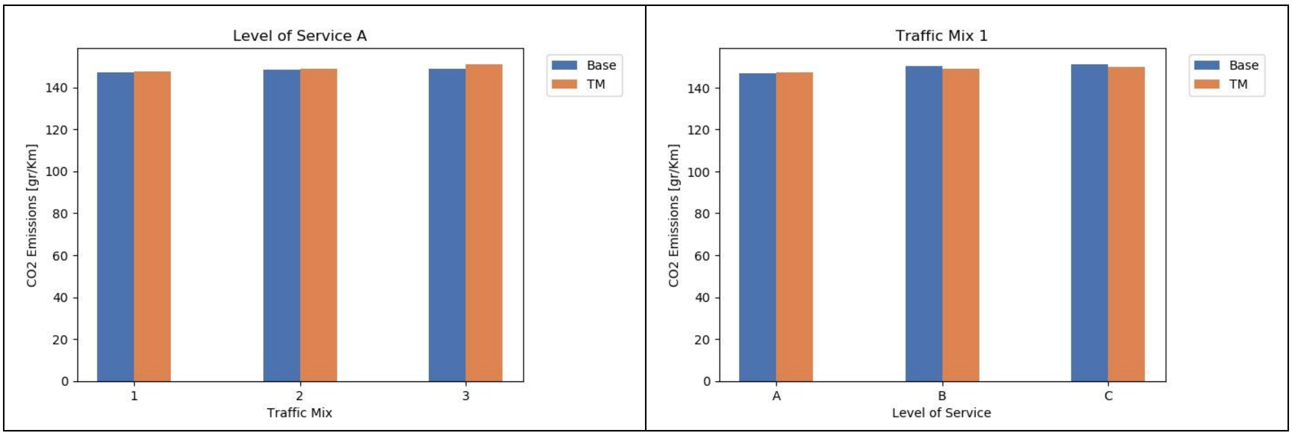


Figure 51: Average number of events with TTCs below 3.0 seconds for use case 5.1 (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

3.1.5.3.3 Environmental impacts

Figure 52 shows the average CO_2 emissions per travelled kilometre for the different vehicle mixes and levels of service as bar charts providing a comparison of the baseline simulation and traffic management service (note that the scaling of average CO_2 emissions is not equal for every chart).

For the baseline simulations, the CO_2 emissions increase for higher LOS and vehicle mixes, which again reflects the modified CAV behaviour in the preparatory phase prior to a ToC. As traffic management Service 5 ensures a smooth traffic operation without notable discrepancies across different LOS and vehicle mixes, the CO_2 emissions per kilometre driven do neither exhibit any significant variations.



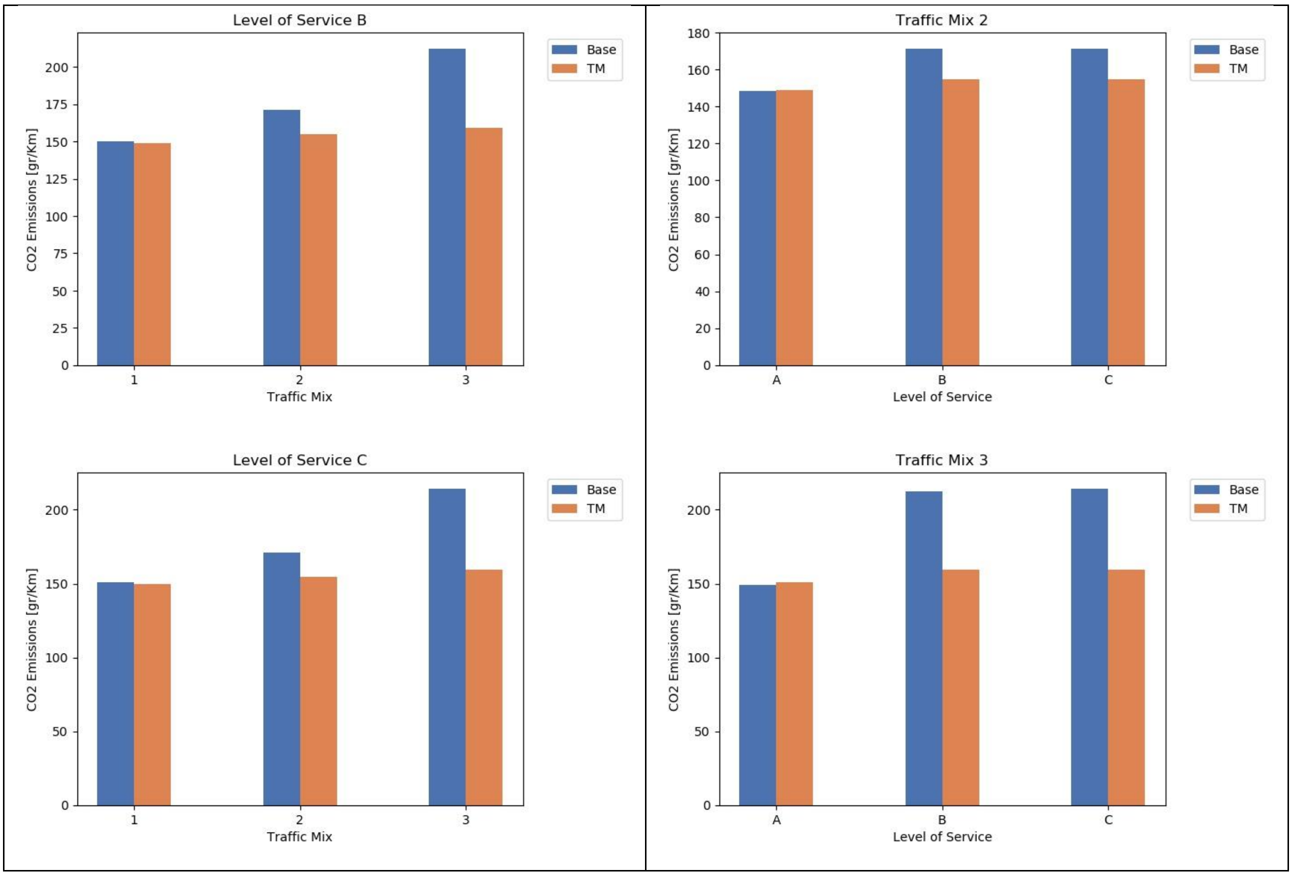


Figure 52: Average CO_2 emissions per kilometre travelled for use case 5.1 (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

3.1.5.4 Discussion

The baseline simulations confirm the hypothesis that a coordinated distribution of takeover events can prevent a drop in traffic efficiency in areas where an accumulated occurrence of transitions may be expected. For the assessment we assumed that in absence of a managed TOR coordination the takeover events will be concentrated closer to the area, where no automated driving is possible. Our simulation results encourage the pursuit of the approach of ToC distribution. As the main reason for the effectiveness of this we identified the prevention of compounding braking efforts occurring if a sequence of CAVs performs transitions to manual driving simultaneously.

Implied by smoother traffic flow the presence of traffic management Service 5 also results in lower CO_2 emissions despite higher average speeds for all scenarios. Regarding traffic safety the results indicate additionally a better overall safety in presence of distributed transitions. That is, far less critical TTC events occurred in comparison to the baseline simulations. This is also a consequence of the smoother flow and smaller variance of vehicle speeds in the case of distributed ToCs.

It should be noted, though, that the parametrisation for the temporary, local efficiency decrease prior to a takeover might be modelled rather harshly when a temporary gap of 3.5 seconds is assumed to be established. However, as long as the ToC preparation involves an enlargement of vehicle headways in some form, the results can be expected to persist qualitatively.

An interesting phenomenon, which seems warrant further investigation, is the non-monotonic dependence of the number of critical events on the share of automated vehicles (see also Figure 51).

3.2 Second iteration

3.2.1 Scenario 1 (Use case 1.3): Queue spillback at exit ramp

3.2.1.1 Introduction

Figure 53 depicts a CAV (blue) and LVs (light-coloured) approach an exit on a motorway. There is a queue on the exit lane that spills back onto the motorway. We consider a queue to spill back on the motorway as soon as there is not enough space on the exit lane to decelerate comfortably (drivers will start decelerating upstream of the exit lane).

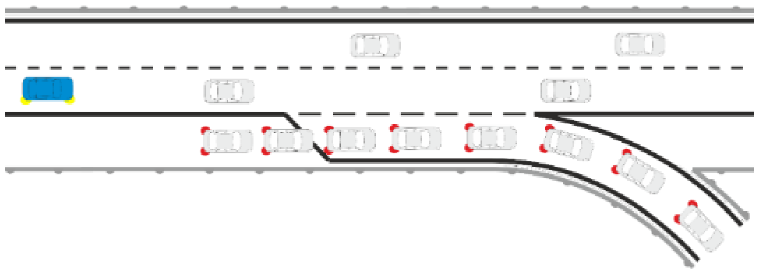


Figure 53: Scenario layout of use case 1.3.

Vehicles are not allowed to queue on the emergency lane, but queuing on right-most lane of the motorway will cause (a) a safety risk due to the large speed differences between the queuing vehicles and the regular motorway traffic, and (b) a capacity drop for all traffic (including vehicles that do not wish to use the exit). In the baseline of this scenario (see also deliverable D3.1) vehicles queue on the main road and the speed limit remains unchanged (drivers/AVs have to decide on their own to slow down when they notice the queue).

3.2.1.2 Traffic management setup

Traffic managers will try to avoid queuing on an exit ramp, usually by taking measures to improve the outflow of the exit. This use case looks into the behaviour of the RSI and the vehicles when the spillback of a queue on the motorway actually occurs. It does not discuss if, when, or how the traffic manager can avoid the spill-back of the queue on the motorway, as this is a different use case.

In the traffic management case, the RSI will monitor traffic operations along the motorway, the off-ramp and exit lane, and when a queue spillback is detected, a section of the emergency lane will be opened. As such, vehicles that wish to exit the motorway will be able to decelerate and queue safely without interfering with the regular motorway traffic. The length of the section of the emergency lane that is opened for traffic will be determined dynamically by the RSI. The speed limit on the main road will also be reduced to increase safety. The reduction of speed limit will be gradual: first the upstream end of the queue is detected. Then we calculate the distance required to decelerate comfortable. Next, we find the first encountered upstream VMS from this point where deceleration would start. At this point we apply a speed limit of 50 km/h. The subsequent upstream VMSs will then in sequence display 70 km/h and 90 km/h (the distance of 250 m between VMSs is sufficient for decelarating comfortably to the next speed limit). This speed limit is reduced to the same speed for all lanes.

The speed limit and the status of the emergency lane (whether or not it is open for queuing) is communicated using both VMSs and V2X (to CVs and CAVs). Because the same restrictions have to apply to all vehicles, the resolution of the VMS's is also used for communication with the C(A)Vs. In the use case, a series of VMS-portals is located at a 250 m interval upstream of the exit lane.

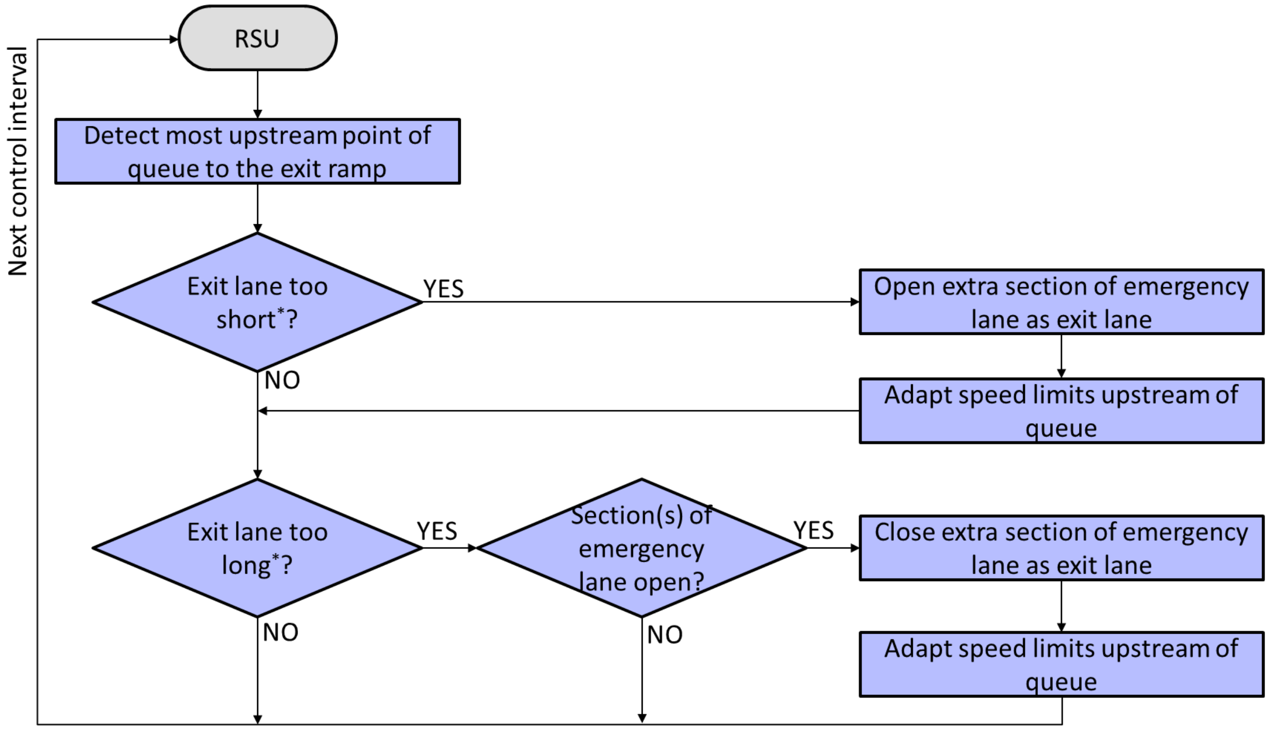
Note that this use case will never issue a TOR. If an AV or a CAV does not manage to change into the exit lane and would be about to issue an MRM, it will have three options:

1) The vehicle stops on the main road, close to the last section where it can change to the exit
2) The vehicle drives past the exit and stops on the emergency lane shortly after the exit
3) The vehicle reroutes and tries to use another exit

Option (1) raises important safety issues and causes an important capacity reduction on the main road, making it therefore not an acceptable choice. Option (2) has no added value compared to option (3). In these both cases, the vehicle will not be able to use the intended exit and need to reroute. Option (3), having automatic rerouting, is clearly the safest and most interesting option. Since an MRM is never the best option, a TOR will also never be issued.

3.2.1.2.1 Traffic management logic

In Figure 54 we show the flow chart for the traffic management logic of use case 1.3.



*: The exit lane is long enough when a vehicle heading for the exit can decelerate comfortably (deceleration of m/s^2) on the exit lane from free flow speed to a full stop at the tail of the queue (+/- xxm). It is too long if the exit lane is longer than this required distance.

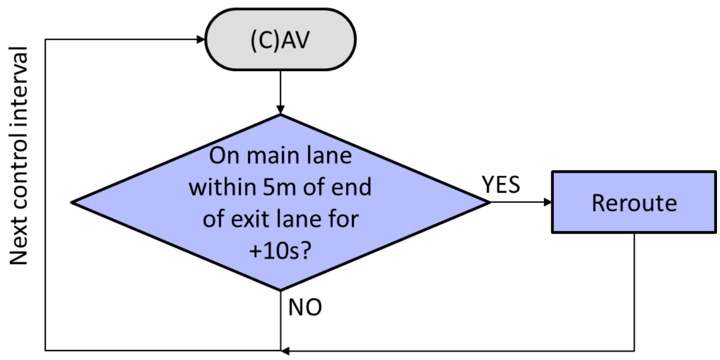


Figure 54: Flow chart depicting the traffic management logic for use case 1.3.

Timeline of actions

1. Detection of queue spillback on the off-ramp
2. RSI continuously monitors the queue (possibly supported by V2X)
3. Demarcate spatial action horizon upstream of the off-ramp
4. The RSI communicates with the traffic stream about the adapted speed limits (dependent on the upstream distance from the tail of the queue):
    a. Via conventional signalling (e.g., VMS) to inform LV drivers and AVs
    b. Using V2X to inform CV drivers and CAVs
2. Desired behaviour of vehicles:
    a. Within the spatial horizon determined by the RSI, the vehicles leaving the motorway are advised to use the emergency lane for decelerating and queuing
    b. Within the spatial horizon determined by the RSI, all vehicles are advised to comply with the speed limit at their actual location
3. If an automated vehicle does not manage to merge into the exit lane:
    a. An AV will try to merge into the queue for the exit. While trying to merge, it continues to drive towards the exit. When the vehicle reaches the most downstream location where it can still take the exit, it will stop and continue to attempt merging into the exit lane for 10 s. If merging is still not successful after 10 s, the AV will reroute using another off-ramp
4. Once vehicles have passed the off-ramp traffic operations continue normally

3.2.1.2.2 Baseline scenario adaptation

During the simulations of the baseline, SUMO did not always manage to release the desired volume of vehicles onto the network. These vehicles were virtually queued outside of the network. Statistics and simulation results were inaccurate for those vehicles. To improve this a number of changes were made:

- The network was expanded
- Changed route parameter ‘*depart_pos*’ from ‘*max*’ to ‘*random_free*’. This allowed to insert a greater vehicle flow into the network
- Trucks entering the network will now always enter on the right lane. In the former baseline scenario trucks could enter the network on both lanes

3.2.1.3 Results

3.2.1.3.1 Impacts on traffic efficiency

Network-wide impacts

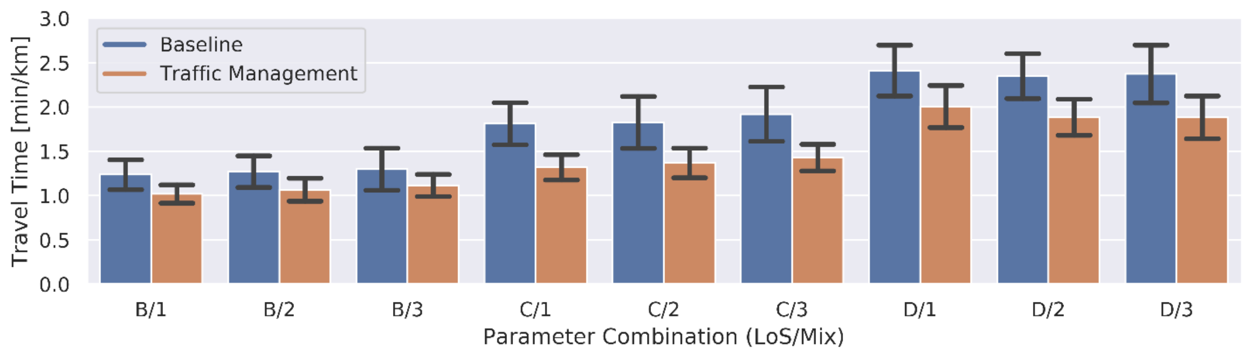


Figure 55 shows how the average travel time on the network increases as traffic density increases. This is as expected. The increase is greater between LOS B and LOS C than between LOS C and LOS D.

The average travel time is lower than the one in the baseline scenario (0.5 minute quicker for LOS D), despite the speed limits applied in the traffic management scenario.

The impact on the travel time due to the extra capacity generated by opening the emergency lane for queuing exceeds the increase caused by the speed limits.

The vehicle mix has a smaller impact on the average travel time, but is still significant. As the share of AVs increases, the queue length for the exit lane increases. This is due to the merging behaviour of the AVs: when they fail to merge, they wait for up to 10 seconds on the main road before they do manage to merge or finally reroute. During this short period they block all upcoming traffic and cause perturbations in the traffic flow on the main road. These perturbations affect both the speed, throughput, and safety.

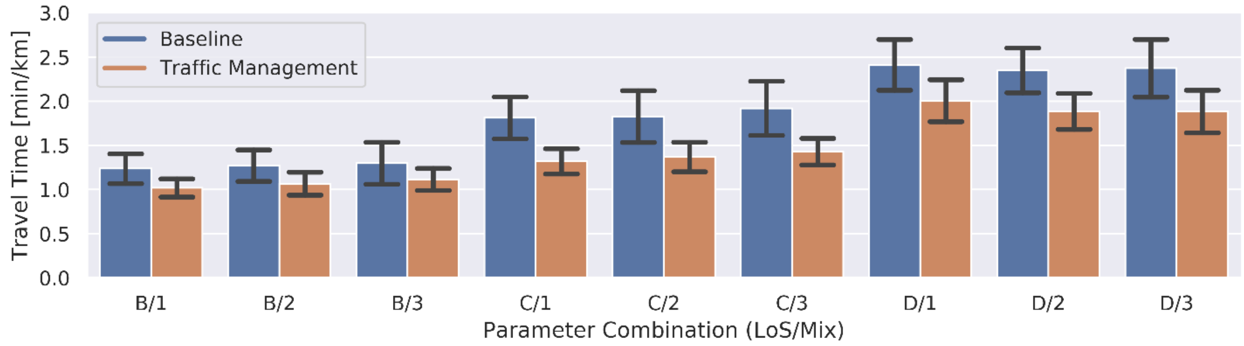


Figure 55: Comparison of the average travel time [min/km] for use case 1.3 simulation experiments between baseline and traffic management (varying the LOS and vehicle mix).

Local impacts

Figure 56 shows four aggregated time-space diagrams per lane. The top row shows the baseline, the bottom row the traffic management scenario. The diagrams on the left show the results for LOS B and vehicle mix 1, the diagrams on the right show the results for LOS D and vehicle mix 1. All diagrams are aggregated over 10 simulation runs with random seeds.

The bottom diagram for LOS B shows that the queue on the lane #1 (exit lane) is stable and limited to a short distance. Traffic on the motorway will locally slow down because of the dynamic speed limit and/or because of vehicles that are trying to merge in the queue for the exit. The speed on the emergency lane (lane 1) is lower than the speed on lanes 2 and 3 (the main road). There is no traffic on the emergency (the emergency lane is closed for traffic), except on a limited distance upstream of the queue.

The bottom diagram for LOS D shows that the queue for the exit lane slowly grows during the simulation. Again, traffic on the motorway will slow down because of the dynamic speed limit (lane 3) and/or because of vehicles that are trying to merge in the queue for the exit (mostly limited to lane 2). The speed on the emergency lane (lane 1) is lower than the speed on lanes 2 and 3 (the main road). There is no traffic on the emergency (the emergency lane is closed for traffic), except on a limited distance upstream of the queue, but the queue is remarkably longer than in the LOS B simulation.

Comparing the baseline with the traffic management scenario, we can see how congestion is significantly reduced on all lanes in the latter one.

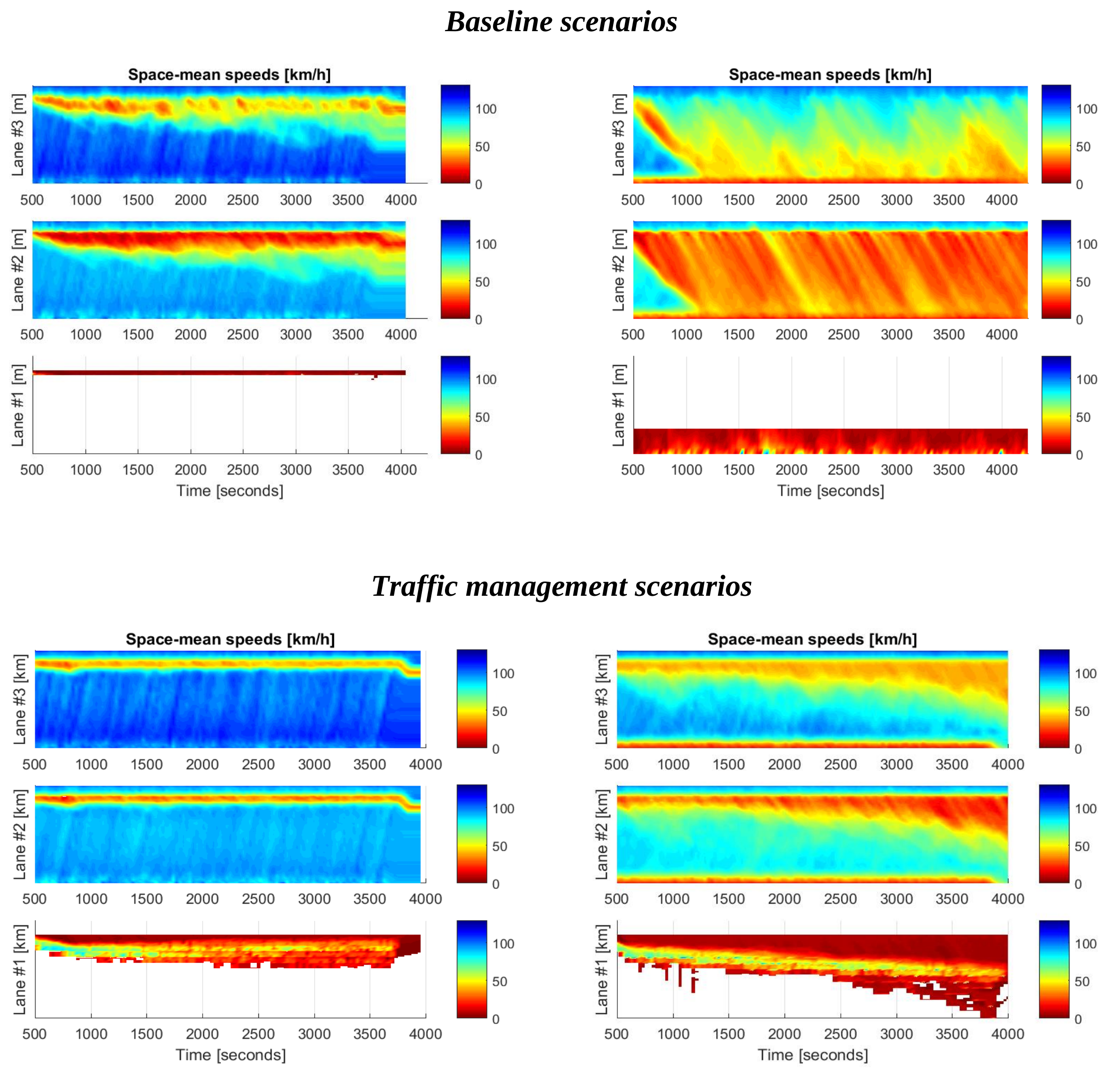


Figure 56: Comparison of the aggregated space-time diagrams per lane for use case 1.3 simulation experiments for LOS B (*left column*) and LOS D (*right column*), both for vehicle mix 1 (each time, *top*: left lane, *middle*: right lane, *bottom*: emergency lane/off-ramp), in the baseline (*top row*) and traffic management (*bottom row*) scenarios.

On the next pages we show groups of time-space diagrams. Each 3 by 3 table contains from left to right LOS B, C, and D, and from top to bottom vehicle mix 1, 2, and 3. In addition, each cell in the table contains three time-space diagrams that represent from top to bottom the left, right, and emergency lane. The first 3x3 table contains the diagrams for the baseline scenario, the second table for the traffic management scenario.

All these time-space diagrams are created by each time averaging the ten randomised runs into a single diagram. This is a powerful technique, because this way, times and locations with recurring phenoma (be it congestion, be it free-flowing traffic) are made visible.

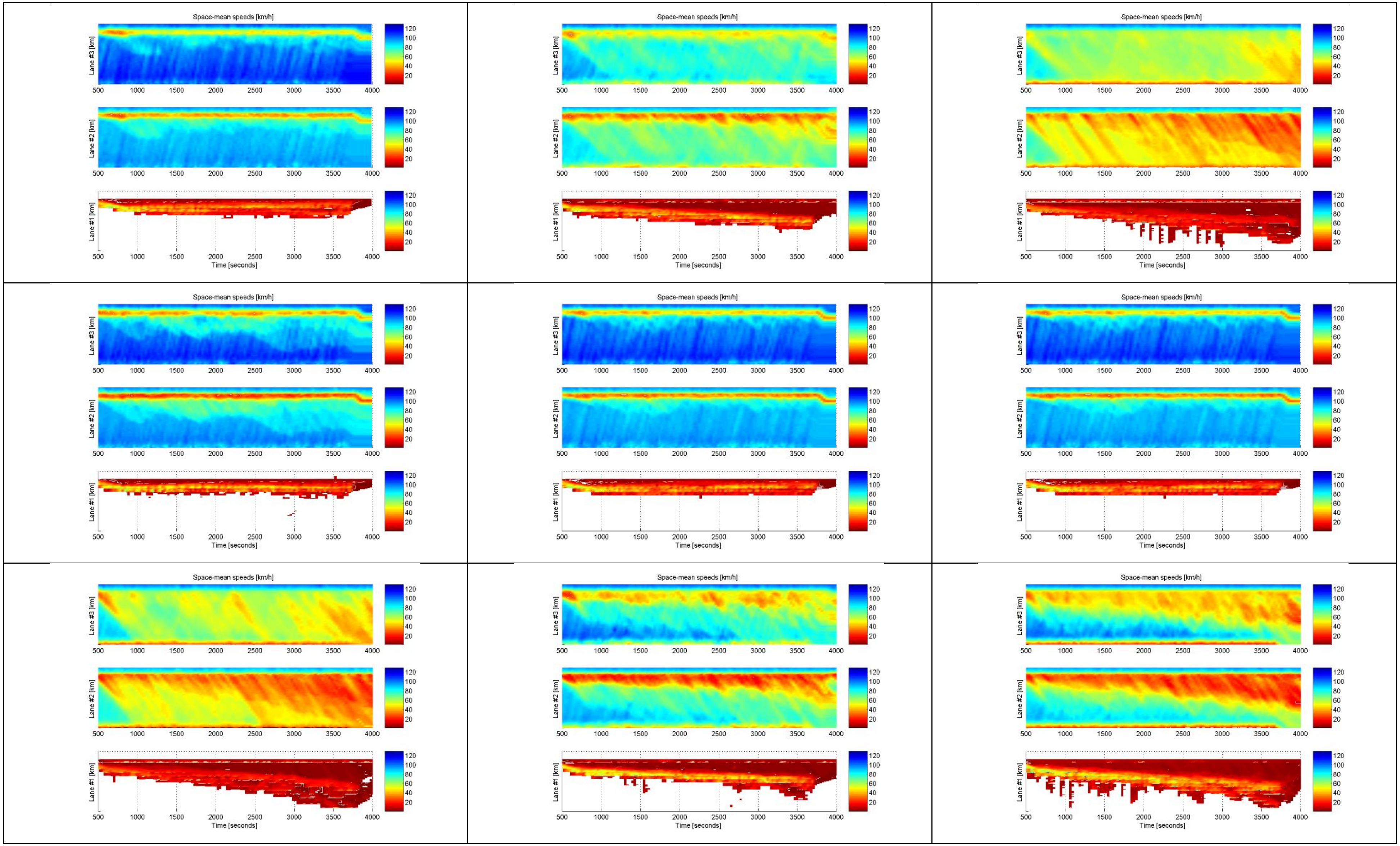
Looking at the different diagrams, we make the following observations about the traffic management scenario in comparison with the baseline scenario:

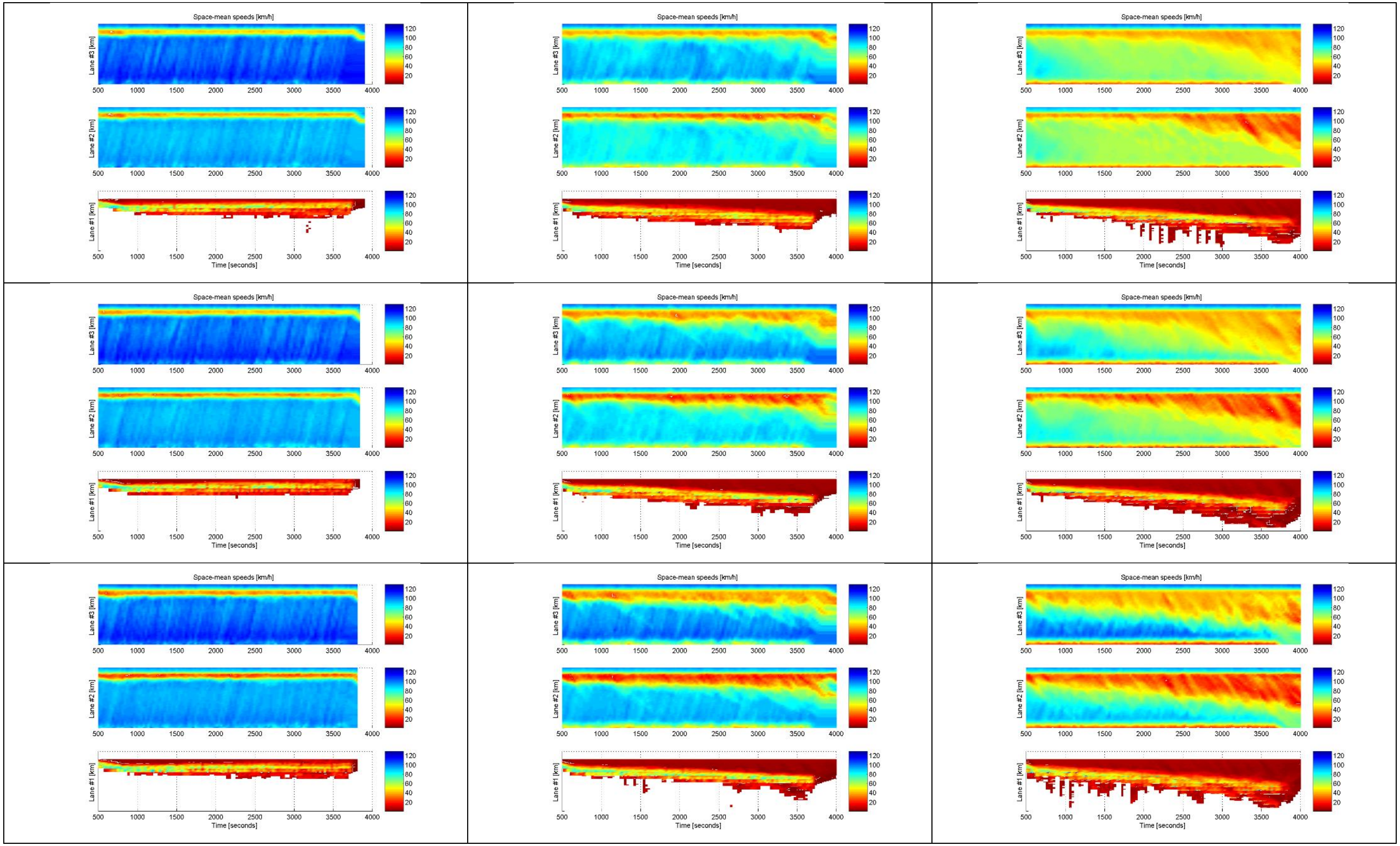
- **Vehicle mix 1:**
  - LOS B:
    - Main lanes + emergency lane: slightly less congestion
  - LOS C:
    - Main lanes: much less congestion
    - Emergency lane: slightly less congestion
  - LOS D:
    - Main lanes: congestion gets distributed over lanes
    - Emergency lane: slightly less congestion

- **Vehicle mix 2:**
  - LOS B:
    - Main lanes + emergency lane: slightly less congestion
  - LOS C+D:
    - Main lanes + emergency lane: considerably more congestion

- **Vehicle mix 3:**
  - LOS B:
    - Main lanes + emergency lane: considerably less congestion
  - LOS C:
    - Main lanes + emergency lane: slightly less congestion
  - LOS D:
    - Main lanes + emergency lane: no noticeable differences

In addition, we also observe how the queue length on the emergency lane seems to increase as the share of (C)AVs increases for LOS B. For LOS D, this effect is much less pronounced.


Space-mean speeds [km/h]
Lane #3 [km]
Lane #2 [km]
Lane #1 [km]
Time [seconds]
500 1000 1500 2000 2500 3000 3500 4000
120 100 80 60 40 20


Space-mean speeds [km/h]
Lane #3 [km]
Lane #2 [km]
Lane #1 [km]
Time [seconds]
500 1000 1500 2000 2500 3000 3500 4000
120 100 80 60 40 20

3.2.1.3.2 Impacts on traffic dynamics

In general, the number of lane changes reduces as the LOS increases (see Figure 57). The traffic dynamics cause within-LOS differences between vehicle mixes, thereby on average not significantly impacting the number of lane changes. There the number of lane changes only slightly decreases from the baseline to the traffic management scenario. Furthermore, in the traffic management scenario, as the LOS increases, the length of the queue for the exit increases. When the average travel speed is higher than 90 km/h, passenger cars will take over trucks. Due to increased congestion at higher LOS (and thus a longer section where a dynamic speed limit of 90 km/h or less is active), the number of take-over manoeuvres is reduced.

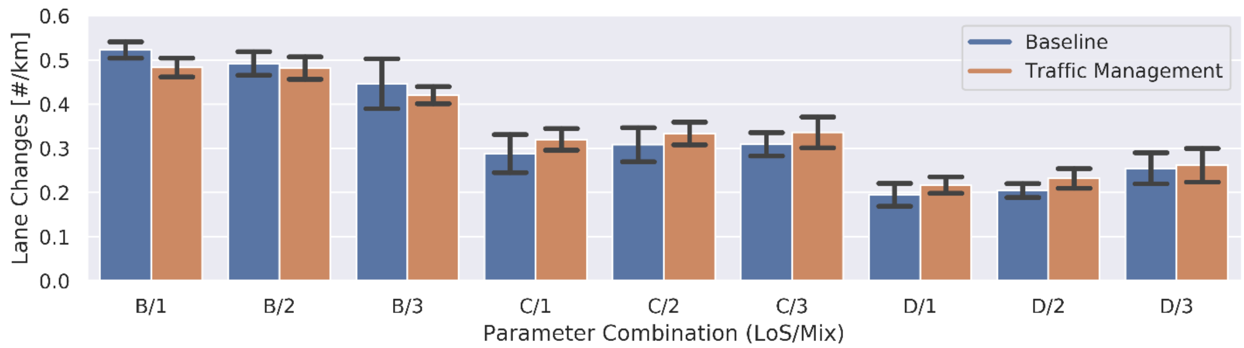


Figure 57: Comparison of the number of lane changes per driven kilometre for use case 1.3 simulation experiments between baseline and traffic management (varying the LOS and vehicle mixes).

The throughput increases strongly between LOS B and LOS C, as shown in Figure 58. There is a small additional increase of the throughput in LOS D compared to LOS C. The increase in throughput between LOS C and LOS D is limited by the capacity of the motorway. There is no significant impact of the vehicle mix on the throughput. Compared to the baseline, the scenario with traffic management has a slightly higher throughput, especially for LOS C and LOS D.

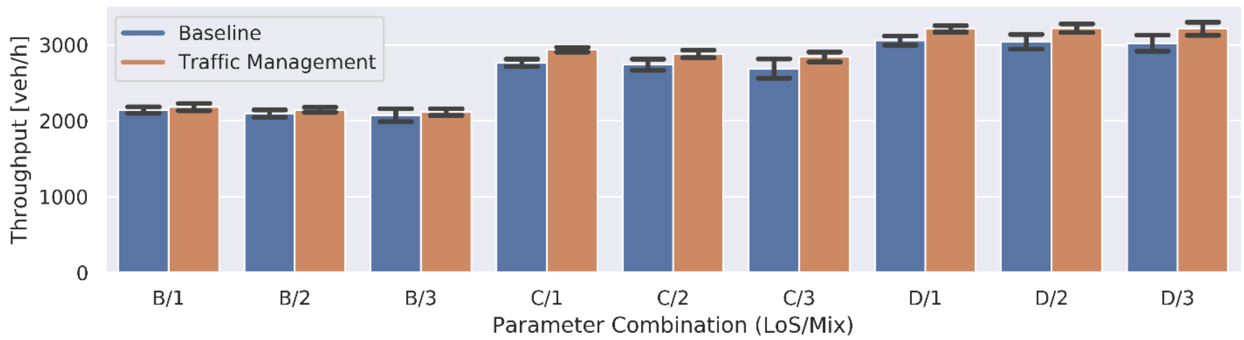


Figure 58: Comparison of the throughput (veh/h) for use case 1.3 simulation experiments between baseline (*top*) and traffic management (*bottom*) (varying the LOS and vehicle mixes).

The occurrence of merge fails decreases as the LOS increases, as shown in Figure 59. As the LOS increases, a longer queue will build up, allowing for a longer section of the emergency lane to open. As the length of the queue increases, a vehicle trying to merge has a longer section in which it can try to merge into the queue for the exit lane. Compared to the baseline, the traffic management scenario exhibits significantly fewer merge fails for LOS B, but more merge fails for LOS C and LOS D. The number of merge fails in the baseline scenario is rather low for LOS C and LOS D. Due to congestion and a long waiting queue in these simulations, the AVs have enough time to merge. In the traffic management scenarios, traffic is fluid even for LOS C and LOS D, which reduces the time to merge and hence causes more merge fails.

The occurrence of merge fails is registered only for AVs. Therefore the number of merge fails increases as the share of AVs in the vehicle mix increases.

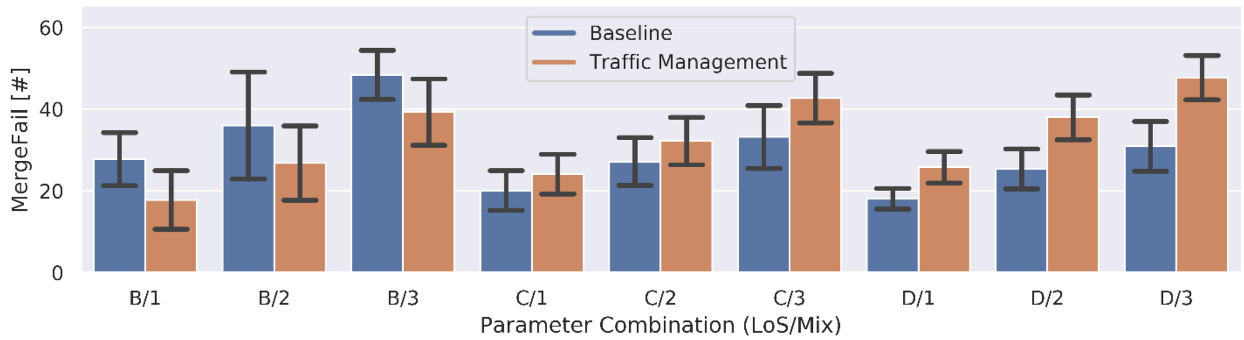


Figure 59: Comparison of the failed merges in to the right target lane for use case 1.3 simulation experiments between baseline and traffic management (varying the LOS and vehicle mixes).

3.2.1.3.3 Impacts on traffic safety

Network-wide impacts

The average number of safety-critical events increases with the share of AVs in the vehicle mix, there is no significant relation with the LOS as shown in Figure 60. Critical events typically occur when there are important speed differences on the network.

There is a significant reduction in the number of critical events in the simulations with traffic management compared to the simulations of the baseline. This is due to the reduction of the queue length and to the use of the dynamic speed limits, which prevent large speed differences between queuing vehicles and vehicles approaching the queue.

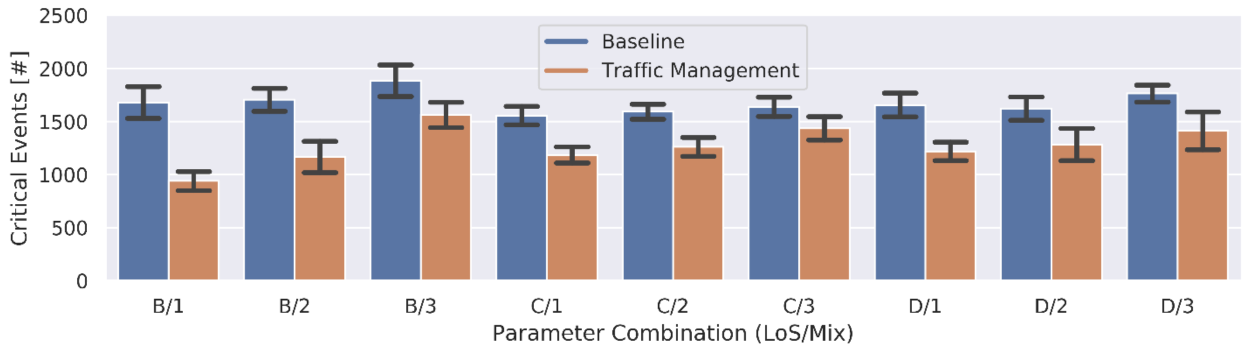


Figure 60: Comparison of the critical events [#/km] (TTC < 3.0 s) for use case 1.3 simulation experiments between baseline and traffic management (varying the LOS and vehicle mixes).

Local impacts

Figure 61 shows the spatial distribution of critical TTC events for the baseline (top graph) and the traffic management (bottom graph) scenarios. There is a small cluster of TTCs at the entry of the network. This is a SUMO-artefact, which is not relevant to be discussed.

The primary occurrence of TTCs is near the end of the queue on the exit lane, and a secondary cluster is near the end of the exit lane on the right lane of the main road. Both occur where fast approaching vehicles encounter slow vehicles that are trying to merge into the queue for the exit lane. As discussed above, the traffic management has significantly reduced the number of TTCs, but it does not prevent them from happening at all. However, compared to the baseline, we can see how there are fewer critical TTC events encountered upstream, because of a more steady flow and resulting in higher traffic safety. These events are also shifted from lanes 2 and 3 towards lanes 1 and 2 at the downstream end of the bottleneck. And furthermore, there are far less critical TTC evens at the upstream end of lane 1.

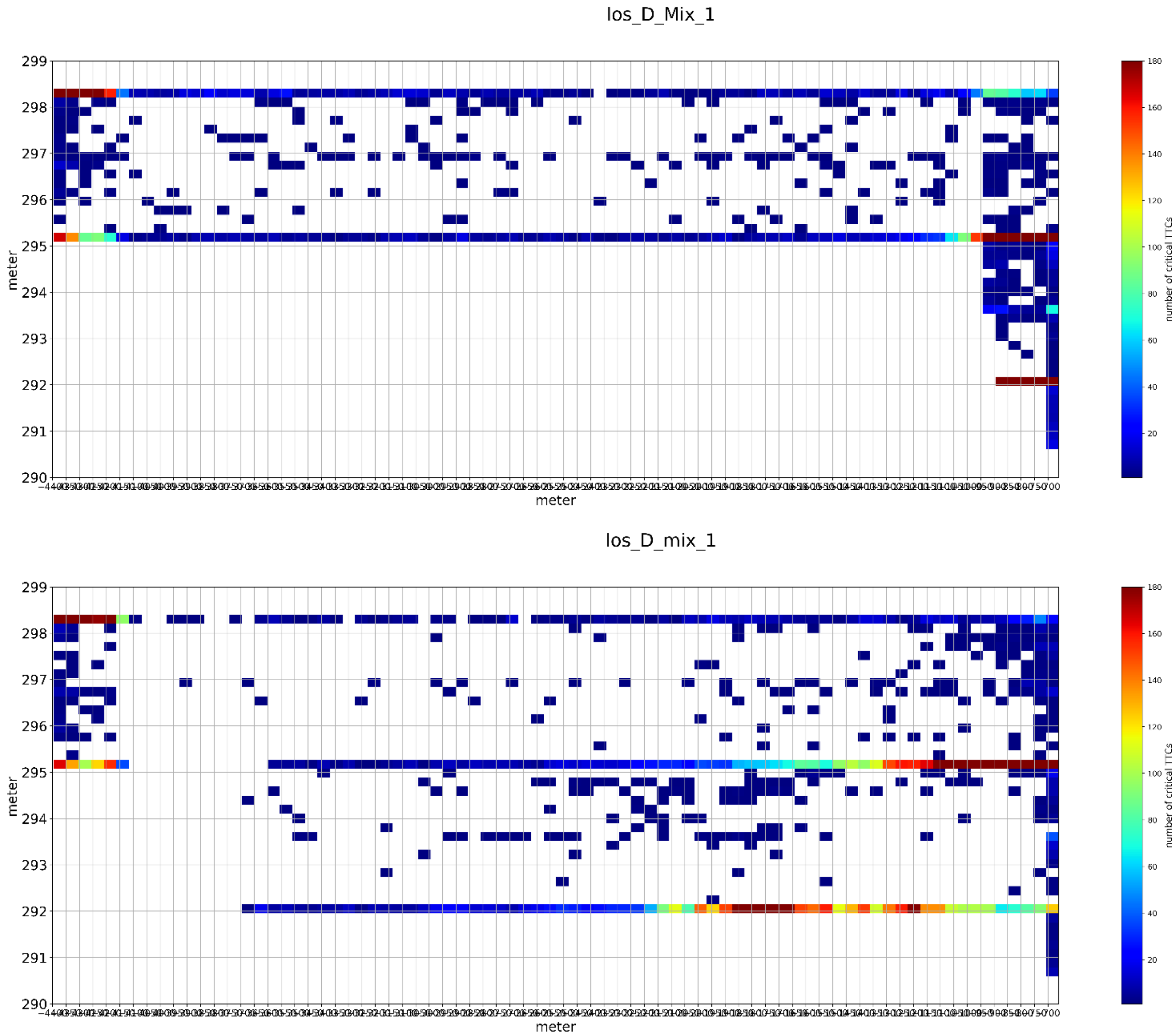


Figure 61: Comparison of the spatial distribution of critical TTCs (< 3 sec) for use case 1.3 and parameter combination D/1 between baseline (*top*) and traffic management (*bottom*). Colours indicate the number of critical TTCs.

3.2.1.3.4 Environmental impacts

CO_2 emissions increase slightly with the LOS and with the share of AVs in the vehicle mix, as shown in

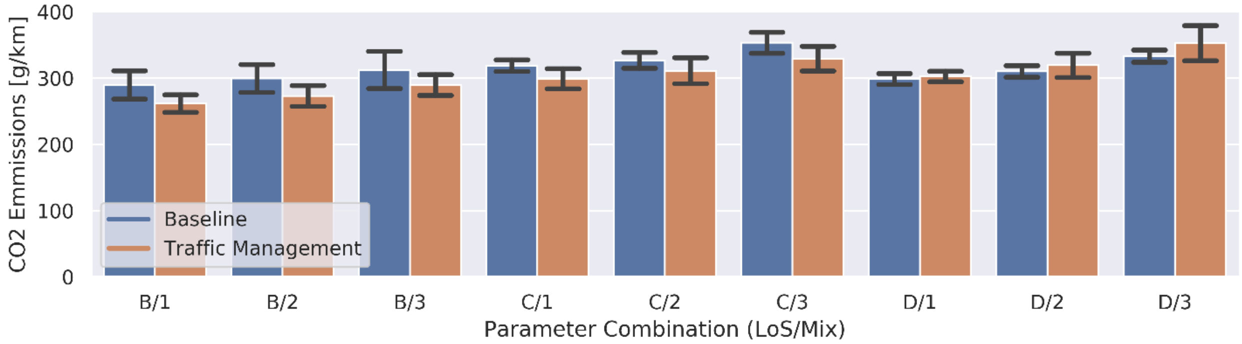


Figure 62. The queue length increases as the share of AVs increases in the vehicle mix. This is discussed in the section on traffic efficiency above. The CO_2 emissions correlate with the queue length, due to stop-and-go traffic in the queues. Compared with the baseline, the traffic management scenario has lower CO_2 emissions across all LOS and vehicle mixes.

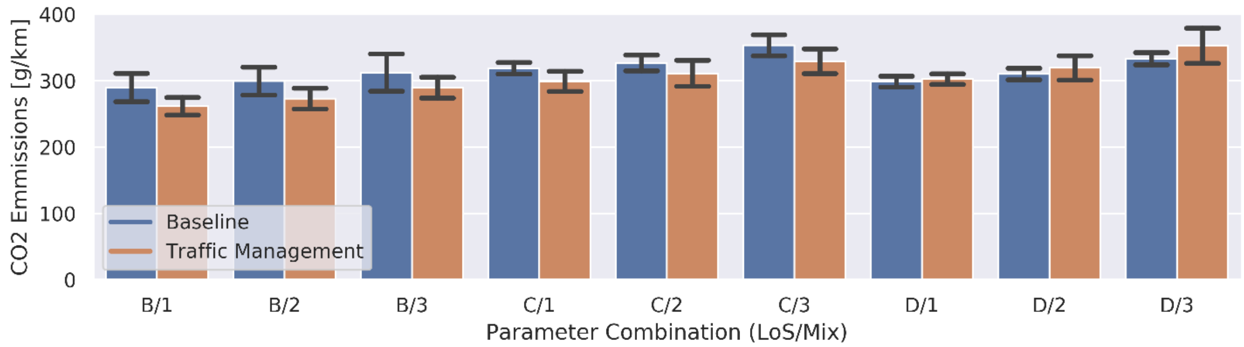


Figure 62: Comparison of the CO_2 emissions [g/km] per driven kilometre for use case 1.3 simulation experiments between baseline and traffic management (varying the LOS and vehicle mixes).

3.2.1.4 Discussion

The simulations with traffic management show a significant reduction of queuing, especially on the main road. This has a beneficial effect on all indicators previously discussed. The average travel time increases, despite the speed limits applied in the traffic management scenario. The impact on the average travel time due to the extra capacity generated by opening the emergency lane for queuing exceeds the increase caused by the speed limits.

The vehicle mix has a smaller impact on the average travel time, but is still significant. As the share of AVs increases, the queue length for the exit lane increases. This is due to the merging behaviour of the AVs: when they fail to merge, they wait for up to 10 seconds on the main road before they do manage to merge or finally reroute. During this short period they block all upcoming traffic and cause perturbations in the traffic flow on the main road.

The number of lane changes reduces as the LOS increases, the vehicle mix does not impact the number of lane changes significantly. The number of lane changes only slightly decreases from the baseline to the traffic management scenario. The throughput increases strongly between LOS B and LOS C in the traffic management scenario. There is no significant impact of the vehicle mix on the throughput. Compared to the baseline, the scenario with traffic management has a slightly higher throughput, especially for LOS C and LOS D.

The occurrence of merge fails decreases as the LOS increases. As the LOS increases, a longer queue will build up, allowing for a longer section of the emergency lane to open. As the length of the queue increases, a vehicle trying to merge has a longer section in which it can try to merge into the queue for the exit lane. The occurrence of merge fails is registered only for AVs. Therefore the number of merge fails increases as the share of AVs in the vehicle mix increases. But compared to the baseline there are less merge fails, as fewer AVs need to reroute.

The average number of safety-critical events increases with the LOS and with the share of AVs in the vehicle mix, but it is still significantly reduced compare to the baseline. As LOS increases, queue length grows, and therefore speed differences and the occurrence of critical events both increase. AVs that cannot find an appropriate gap in the queue to merge can stop on the main route for up to 10 seconds until they finally merge or finally reroute. These vehicles cause perturbations on the lanes of the main road, which can cause TTCs.

CO_2 emissions increase slightly with the LOS and with the share of AVs in the vehicle mix. The queue length increases as the share of AVs increases in the vehicle mix. The CO_2 emissions correlate with the queue length, due to stop-and-go traffic in the queues.

3.2.2 Scenario 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice

3.2.2.1 Introduction

CAVs and LVs travel on the motorway mainline, whereby CAVs that travel on the on-ramp can use an intelligent ramp metering system at the entrance of the on-ramp.

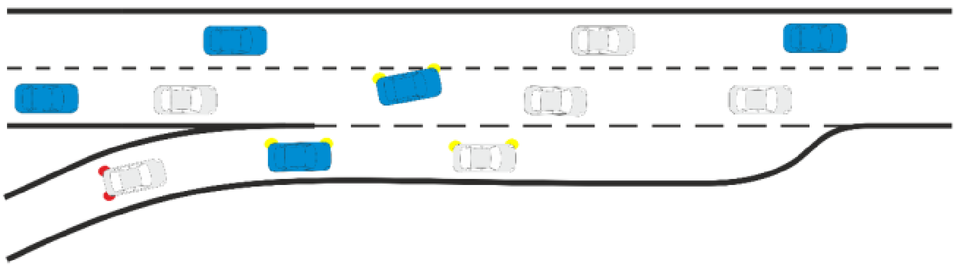


Figure 63: Scenario layout of use case 2.1.

The underlying algorithm of the ramp metering is provided by the merging assistant system. The algorithm calculated merging gaps and speed advices for CAVs on the on-ramp during TransAID's first iteration. For its second iteration, the algorithm is enhanced with pairing an on-ramp CAV and a mainline C(A)V, hence speed advices for the mainline C(A)V to open gaps are implemented as well, under the assumption that speed advices for the on-ramp CAV and mainline C(A)V are supported with 100% compliance rate.

3.2.2.2 Traffic management setup

The baseline scenario of D3.1/2nd iteration is set up on the same scenario description above but without traffic management measures, i.e. no merging assistant system nor ramp metering. On-ramp CAVs (75% group A, 25% group B) approach the mainline motorway, which includes road participants (LVs, heavy and light trucks, CVs, and CAVs (75% group A, 25% group B)).

The normal scenario of D4.2/1st iteration is set up on the same scenario description above, with the merging assistant system on, but no ramp metering. On-ramp CAVs (100% group A) approach the mainline motorway, which includes road participants (LVs, CVs, and CAVs (100% group A)).

The traffic management scenario of D4.2/2nd iteration is set up on the same scenario description above, with both traffic management measures: (a) the enhanced merging assistant system to provide speed advices for the on-ramp CAVs and the mainline C(A)Vs, and (b) the ramp metering (merging assistant system as the underlying algorithm) to control on-ramp flow, provide speed advices, and assist successful merging behaviour with minimum ToC occurrence.

With the objective of consistent results comparison, the three scenarios of D4.2/2nd iteration is set up and further discussed in Section 3.2.2.3.

3.2.2.2.1 Traffic management logic

Zoning adaptation

The traffic management zoning is first defined. Due to the most significant change of adding intelligent ramp metering, the important points and sub-areas are updated here in Figure 64, which are explained in the following with the rationale behind them:

Points

- Ramp metering (-978, 0)
- Main road entry detectors (-1800, 0)
- On-ramp detector (-980, 0)
- On-ramp queue detector (-1180, 0)
- First Merge Point (FMP) (-500, 0)
- Merge Decision Point (MDP) (-435, 0)
- Lane Drop Point (LDP) (0, 0): this is also the camera set-up point; camera detection distance is (-600~0, 0)
- Control revoke point (50, 0)

Sub-areas

- Merging zone (-500~ -435, 0)
- Transition Area (TA)+ Minimum-Risk Manoeuvre Zone (MRM-Z) (-435, 0)
- Hypothetical gap searching Zone, ca. (-1260, -1800)

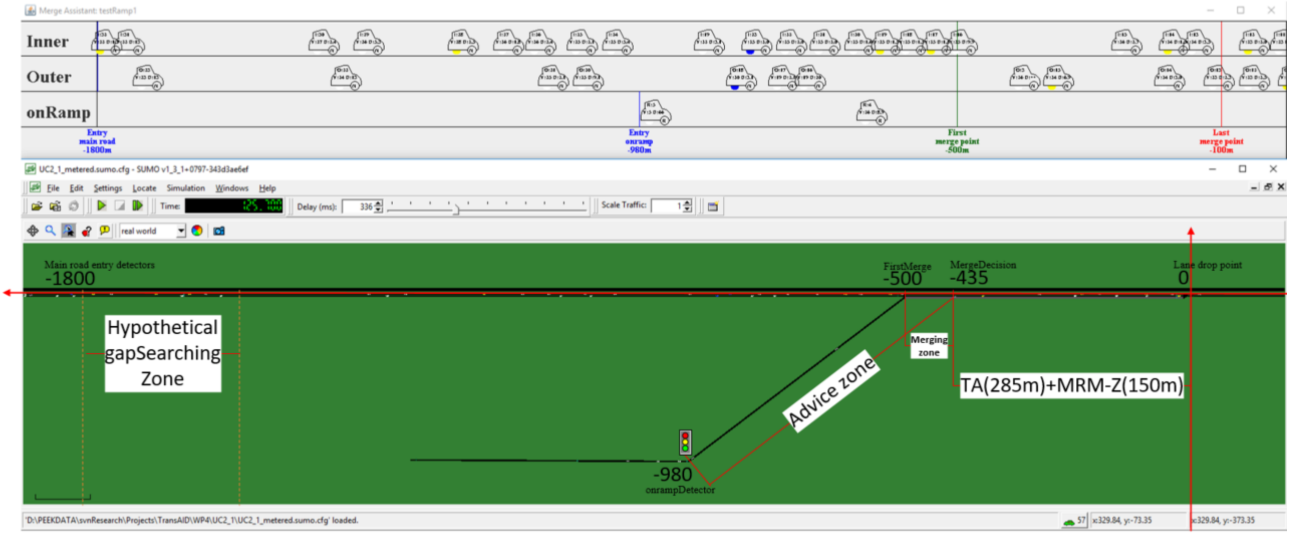


Figure 64: Zoning indication of the SUMO network for use case 2.1.

As a continuation from D4.2/1st iteration, the SUMO simulation network is directly used and the GUI of the merging assistant system is shown in the upper graph, which corresponds to the SUMO simulation at run-time.

For TransAID Task 6.2, an additional simulation component will be simulated in UC2.1 to investigate the infrastructure reactions regarding integration of simulation components. The implementation of the intelligent ramp metering in SUMO and its related traffic management strategy are the key changes. With the given traffic complexities of giving cooperative speed advices to mainline C(A)Vs and on-ramp CAVs under the control of the intelligent ramp metering, Figure 64 shows the new zoning indication according to the service's requirements and the individual vehicle kinematics.

The underlying initial gap searching and speed advices calculation of the merging assistant system, with and without the combination of ramp metering are both applicable with this Figure 64. The apparent difference is the position of the hypothetical gap searching zone: in the case of with ramp metering, the on-ramp CAVs encounter possible delays or full stops in front of the ramp metering, which cost them more time to accelerate to the advice speed. Therefore the hypothetical gap searching zone is further upstream compared to the case without ramp metering.

Comparing to D4.2/1st iteration, the same TA and MRM zones have been reserved for transition area distance and MRM distance in this iteration. If the ramp metering is on, although traffic compositions here are kept the same as Table 40 in D3.1/2nd iteration, the *dynamicToCThreshold* is set to Merge Decision point (-435, 0) latest, instead of a normal distribution due to the supposedly harder safety control of ramp metering.

Traffic management strategies adaptation

The following traffic management strategies were proposed and implemented (a. to c.) in D4.2/1st iteration. The current developments and implementation of these traffic management strategies are updated below:

a. ToC and MRM fail-safe
b. Merging guidance
c. Lane advice on the mainline left lane (only implemented in the *mergingAssistant* system with *innerLaneHold* to achieve merging model accuracy, is not applicable for message transmission (WP5) and Demo (WP7))
d. Cooperative speed advices to paired vehicles for gap creation
Strategy d. gives speed advice to the mainline CAVs, CVs and to the on-ramp CAVs, to create gaps and assist merging.
e. Intelligent ramp metering
Strategy e. implements a ramp metering with the merging assistant system as underlying algorithm instead of commonly used ramp metering algorithm, such as ALINEA, DC etc. The ramp metering only gives green (1.5 sec) when a regular gap (see the following flow chart) is found.
f. Cooperative lane advice for gap creation (not implemented)
Strategy f. gives lane advice on the mainline vehicles to create gaps for mergers.

As mentioned, while traffic management strategies (a) to (c) are implemented through the merging assistant system in D4.2/1st iteration, strategies (d) and (e) are investigated here in the 2nd iteration.

Strategy (d) is implemented via the enhanced merging assistant system with pairing and gap creation. Strategy (e) is controlled via the same system, but the ramp metering only gives green when a regular gap is found using the merging assistant system and complimented with the enhanced merging assistant system when this gap is not anymore applicable as travel time step increments.

Therefore, some adaptations of the traffic management strategies 'recipes' are made through the development of the enhanced merging assistant system and ramp metering, because we anticipate the intelligent ramp metering would be efficient for gap searching and pairing, that aims at minimising ToC/MRM. These adaptations are being tested out here and it also provides the reasons for the further scenario setup.

Table 14: Traffic management strategies solution under TM 1-3 and LOS B-D (update of D4.2/1st iteration).

Vehicle mix	LOS B	LOS C	LOS D
1	d + e	d + e	d + e
2	d + e	d + e	d + e
3	d + e	d + e	d + e

Traffic management flow chart

With the newly emerged additional simulation component – ramp metering (required in Task 6.3 as well), the flow chart of traffic management application needs to undergo adaptations so that ramp metering algorithm can be fused into the merging assistant system flow chart. In addition, the pairing algorithm is added as an enhancement to the merging assistant system.

The module Merging Assistant On is the core condition of Calculate Advice module. As results, three options are derived from calculating an advice: 1. Regular gap found; 2. Regular gap not found, A pair found; 3. Regular gap not found, No pair found; 4. Regular gap not found, A pair found but rejected. The fourth one is greyed out and shown as dashed line in Figure 65 because it is excluded from our investigation as we assume a 100% compliance rate.

This traffic management flow chart will be further explained with the timeline of actions in the next section.

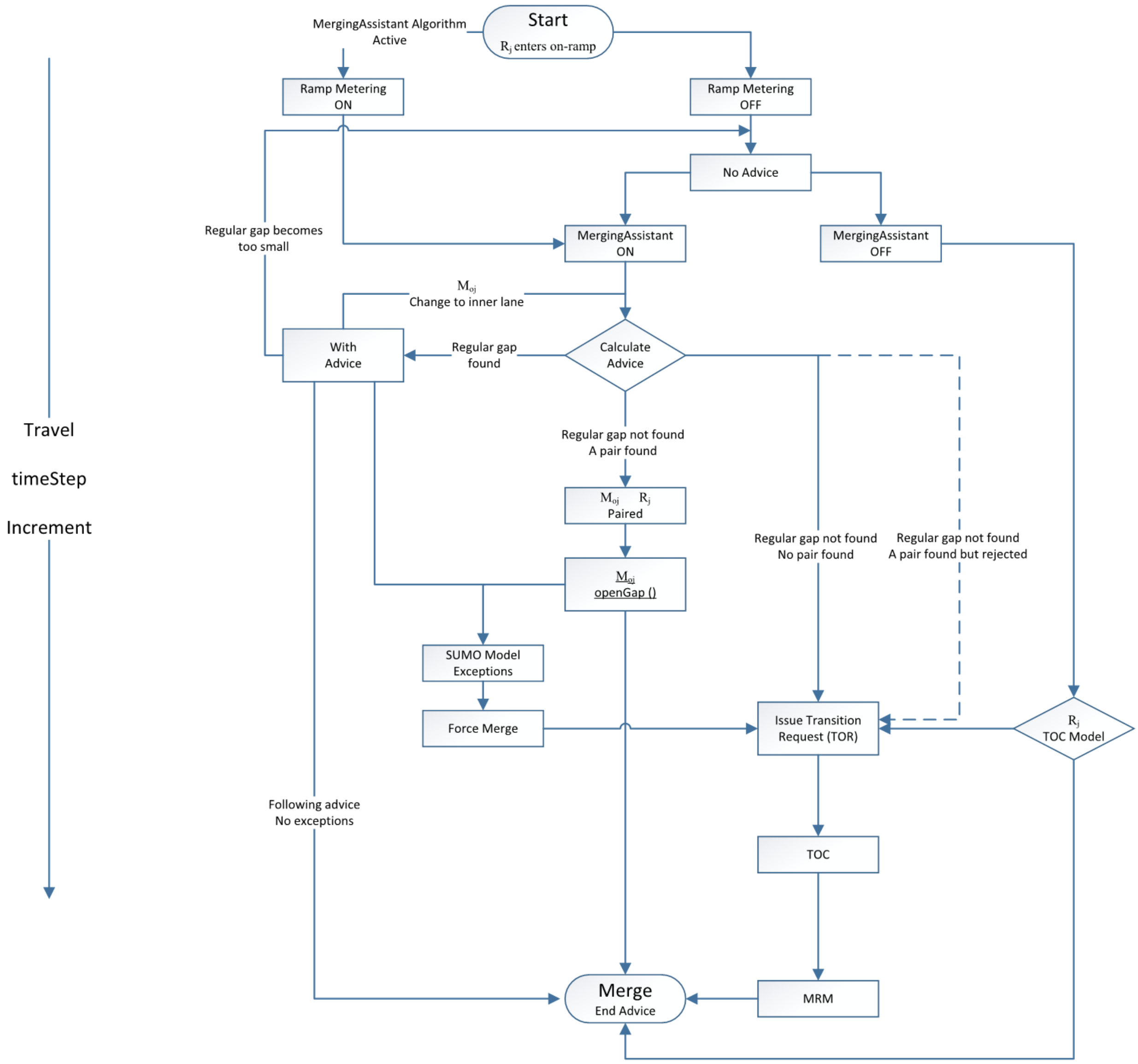


Figure 65: Flow chart of traffic management application for UC 2.1.

Timeline of actions

1. RSI that contains the merging assistant system resides in multiple locations along the motorway merging route. As a component of the RSI, an intelligent Ramp metering contains the merging assistant system as well. The ramp metering continuously monitors:
    a. The mainline CAVs and CVs that enter the hypothetical gap searching zone; the headings, speeds, and positions of these vehicles
    b. The on-ramp CAVs that enter the pre-on-ramp; the speeds, positions, and Projections of driving mode status (should be only automated at the current implementation)
    c. Vehicles in (a) are projected to the merging zone (-500~ -435, 0), assuming they keep on driving in current states with current speeds and no lane changes
2. The ramp metering is modelled as a regular traffic signal controller with the cycle and phases that resemble an operational ramp metering on the motorway:
    a. AMBER_TIME = 1 sec
    b. GREEN_TIME = 1.5 sec

    c. MIN_RED = 1 sec

3. Aiming for optimal efficiency, the basic rule of the ramp metering is to constantly looking for available merging gaps in the platoon of projected virtual vehicles, after a minimum red phase. If a regular gap is found (no pairing needed), the ramp metering will give green for 1.5 second and release an on-ramp CAV
4. On the mainline, considering a regular gap: the leader (could be all types of vehicles; note that RSI will retrieve the relevant data of LVs via induction loops and camera) and the follower (only CAV or CV) continuously send their current positions, speeds, and headings to the ramp metering
5. The merging assistant system continuously evaluates this regular gap at run time:
    a. Calculates the individual speed advice for the on-ramp CAV that the ramp metering just released
    b. Sends the speed advice to the on-ramp CAV and updating it every time step
6. The on-ramp CAV follows the speed advice and adjust its speed accordingly, to achieve successful merging at the calculated merging position inside the merging zone
   It updates the speed and position to the RSI
   If no exception happens, the on-ramp CAV merges successfully
7. If the regular gap becomes too small, lost or cutting-in due to lane changes, the merging assistant system begins to look for possible gaps in (1.a), to find a potential gap with a CAV or CV as follower who could decrease speed and create an acceptable gap for the on-ramp CAV. Afterwards, if a pair is found, the merging assistant pairs the on-ramp CAV and the mainline CAV/CV
8. Repeat (5), calculates and sends speed advice to the pair: on-ramp CAV (adjust speed to meet the new gap) and the mainline CAV/CV (to decrease speed to create the new gap); rejection of pairing by the mainline CAV/CV is not modelled here
9. If (8) fails, the merging assistant system issues a TOR, the on-ramp CAV enters the ToC preparation phase
    a. The merging assistant system relinquishes speed advice over the CAV
    b. If the on-ramp CAV is a group A CAV, it performs ToC (consequent MRM) following the group A CAV parameters
    c. If the on-ramp CAV is a group B CAV, it performs ToC (consequent MRM) following the group B CAV parameters
10. Since merging assistant and ramp metering are reinforced traffic management measure that have exhausted all possibilities, it is highly likely that the on-ramp CAV goes into ToC and consequent MRM in the TA+MRM zone if (9) is executed
11. The on-ramp CAV merges in manually driving mode, inducing a local shock wave at lane drop point

3.2.2.2.2 Baseline scenario adaptation

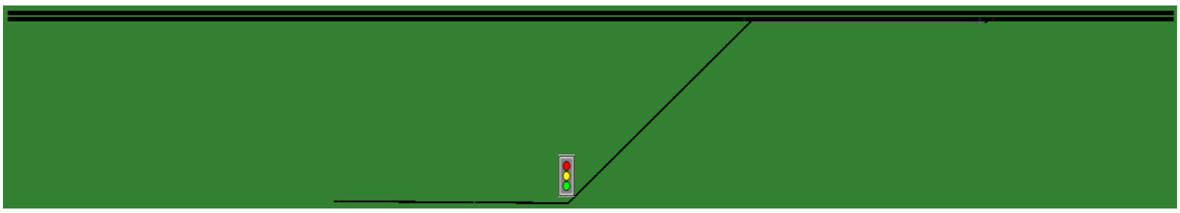
For D4.2/2nd iteration here, the baseline scenario needs to be adapted to implement the additional traffic management component – the ramp metering.

Comparing with Table 4, Table 15 shows the adapted network configuration details with changes marked in yellow. The major change is to add an intelligent ramp metering with a fixed cycle time. The ramp metering can be switch on and off based on the objectives of traffic management strategies.

Table 15: Adapted Network configuration details for use case 2.1. Changes in yellow.

UC 2.1	Settings	Notes
Road section length	• Highway: 2.5 km • On-ramp: 1.0 km • Acceleration lane: 0.5 km	
Motorway direction	• Double direction	
Road priority	3	
Allowed road speed	• Highway: 27.78 m/s • On-ramp: 27.78 m/s	• Highway: 100 km/h • On-ramp: 100 km/h
Number of nodes	7	• jun1 - jun7 priority nodes
Number of edges	6	
Number of O-D relations (routes)	2	• from jun1 to jun7 • from jun3 to jun7
Number of lanes	1-2-3-2	• 1 lane on-ramp • 2 normal lanes on highway • 3 lanes at merging zone (from jun4 to jun5, including acceleration lane) • 2 lanes downstream of the merging zone. Thus, a lane drop from 3 to 2 lanes at the end of merging zone.
Filenames	• Network: UC2_1_metered.net.xml	
Merging area length	65 meter	[First Merge Point, Merge Decision Point]
Ramp metering	• Network: onRamp.json	a. AMBER_TIME = 1 sec b. GREEN_TIME = 1.5 sec c. MIN_RED = 1 sec

Network layout



Road segments

jun1→ jun2: Insertion and speed stabilisation area (100 m→1100 m, 2 lanes)

jun2→ jun4: mainline motorway (500 m, 2 lanes)

jun3→ jun4: on-ramp (500 m→1000 m, 1 lane)

jun4→ jun5: mainline motorway with acceleration lane (500 m, 3 lanes)
jun5→ jun6: mainline motorway (300 m, 2 lanes)
jun6→ jun7: exit (100 m, 2 lanes)

3.2.2.3 Results

3.2.2.3.1 Impacts on traffic efficiency

Following the same result analysis approach, traffic efficiency will be analysed network-wide and locally as in the first iteration.

Network-wide impacts

Figure 66 shows the average network speed of baseline (blue bar), TM0 (orange bar), and TM (green bar) for three LOS B, C, and D, and for three vehicle mixes 1, 2, and 3. This KPI provides a comparison of traffic efficiency on the whole network among three scenarios with different degree of traffic management intensity.

The average network speed is slightly reduced for both TM0 and TM, where the motorway merging is under presence of the traffic management measures. The illusion of an inefficient traffic management logic must be eliminated by the main goal of TM0 and TM: to prevent the ToC and assist safe motorway merging. In some instances, there is no safe merger gap at the current simulation time step, and the merging assistant will keep on searching with each simulation time step increment until it finds one, and then provides speed advice (probably a slower speed than baseline). And for ramp metering, an on-ramp CAV would come to a full stop in front of the ramp metering until the ramp metering find a safe gap for merging.

The slight decrease of average network speed from TM0 to TM can also be supported by the reasoning here: the time loss on the on-ramp when a stricter traffic management is implemented.

The patterns of decreasing average network speed are consistent for all LOS/Mix parameter combination. A non-significant decrease across all combinations also show that the speed is near free-flow speed.

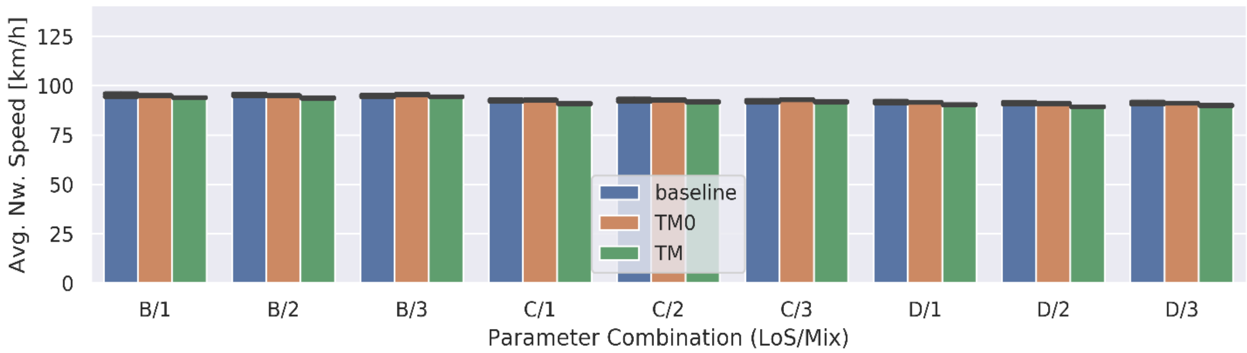


Figure 66: Average network speed [min/km] for use case 2.1 simulation experiments (varying LOS and vehicle mix).

Figure 67 shows the travel time of baseline (blue bar), TM0 (orange bar), and TM (green bar) for three LOS B, C, and D, and for three vehicle mixes 1, 2, and 3. In accordance with the average network speed, the KPI travel time provides the same comparison results of traffic efficiency on the whole network among three scenarios. And it confirms the correlation between average network speed and travel time.

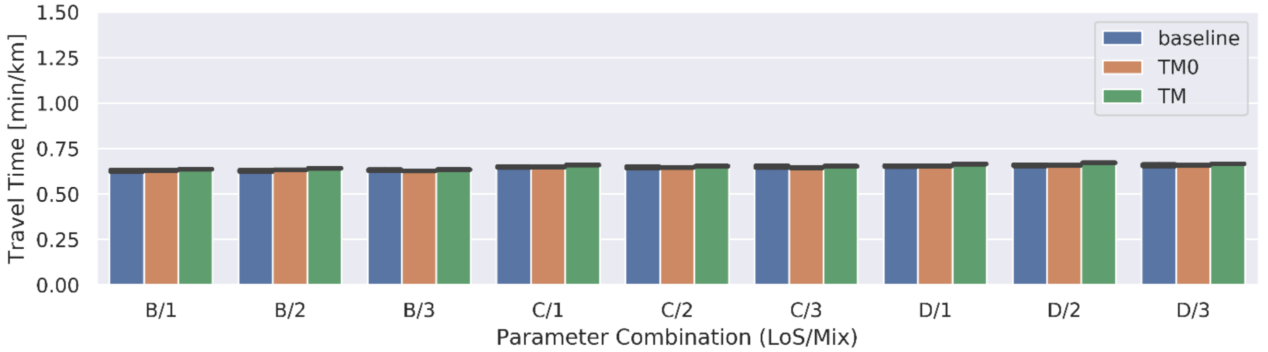


Figure 67: Travel time [min/km] for use case 2.1 simulation experiments (varying LOS and vehicle mix).

Local impacts

Since the local impacts of baseline are already discussed in D3.1/2nd iteration, we focus on the local impacts of the TM scenario in this iteration. Thus, Figure 68 shows the speed and flow spatio-temporal diagram of the TM scenario locally.

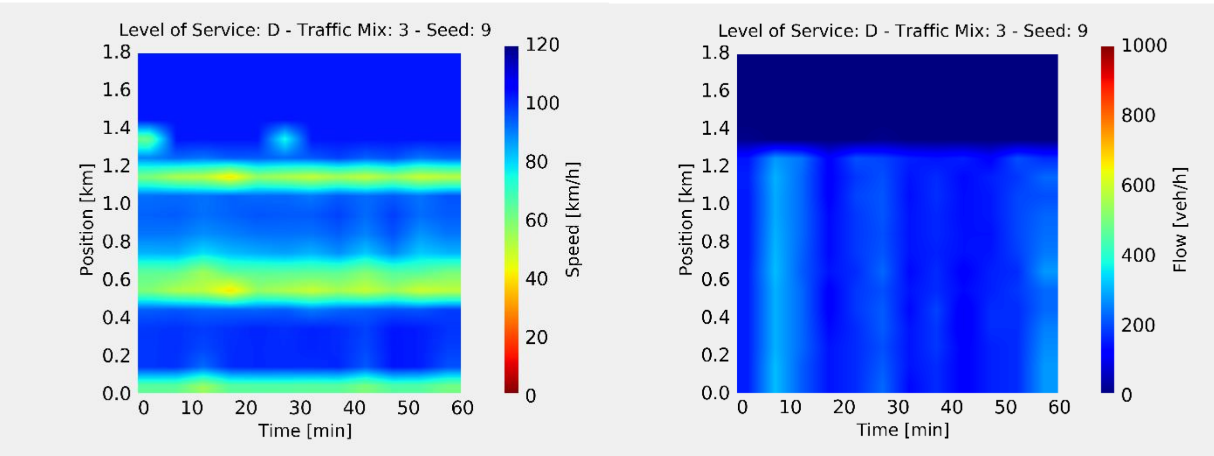


Figure 68: Example time-space-diagrams (on-ramp) of measured speeds (left) and flows (right) for TM (ramp metering) scenario, for use case 2.1 (LOS D, vehicle mix 3, seed 9).

From this figure, we can clearly identify the lower speed regions on the on-ramp: the injection of vehicles at on-ramp entrance, the ramp metering installation position around 0.5 km, and the merging zone around 1.0 to 1.2 km. While the first one is due to SUMO model exceptions and shall be excluded from discussion here, the second one is because of the added ramp metering, which can stop vehicles to wait for a safe gap or a potential pair, and therefore results to lower speed. The third one is at the merging zone, where merging behaviours (possible speed advice with a lower speed to create gap), potential ToC and consequent MRM can take place.

The flow diagram on the right shows less and more subtle changes on individual on-ramp CAV behaviour. A clear division can be identified before and after the merging zone at 1.3 km.

3.2.2.3.2 Impacts on Traffic Dynamics

Figure 69 shows the total number of lane changes of baseline (blue bar), TM0 (orange bar), and TM (green bar) for three LOS B, C, and D, and for three vehicle mixes 1, 2, and 3. This KPI: the number of lane changes per travelled kilometre is used to show the disruption caused in the traffic flow by lane change manoeuvres.

For the baseline (blue bar), within a fixed demand level, the total number of lane changes decreases slightly when the CAV share on the mainline increases. The possible logic here is that, the parameter $lcAssertive$ of CAVs/CVs is smaller compared to LVs. This could lead to less willingness to perform lane change manoeuvres in the TAs, which in turn contributes to slight reduction of the total number of lane changes.

The impact of TM0 and TM on traffic dynamics can be captured through the decrease of the total number of lane changes and decrease of variation among seeds, comparing to baseline scenario. The difference between TM0 and TM is not obvious as one can predict because the TM with a ramp metering installation is using the same merging assistant system algorithm as TM0.

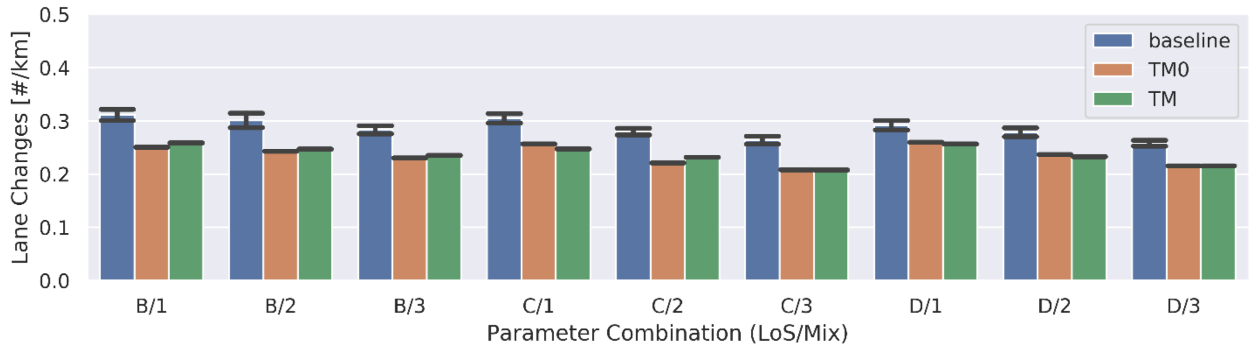


Figure 69: Lane Changes [#/km] for use case 2.1 simulation experiments (varying LOS and vehicle mix).

Figure 70 below shows the throughput of baseline (blue bar), TM0 (orange bar), and TM (green bar) for three LOS B, C, and D, and for three vehicle mixes 1, 2, and 3.

Comparing to baseline, the throughput for scenario TM0 and TM has minimum changes across traffic management intensity on the one hand, and on the other hand, the throughput variation between seeds for TM0 and TM is less than baseline due to the control logic of traffic management, which could have improved traffic heterogeneity in a mixed traffic situation during motorway merging.

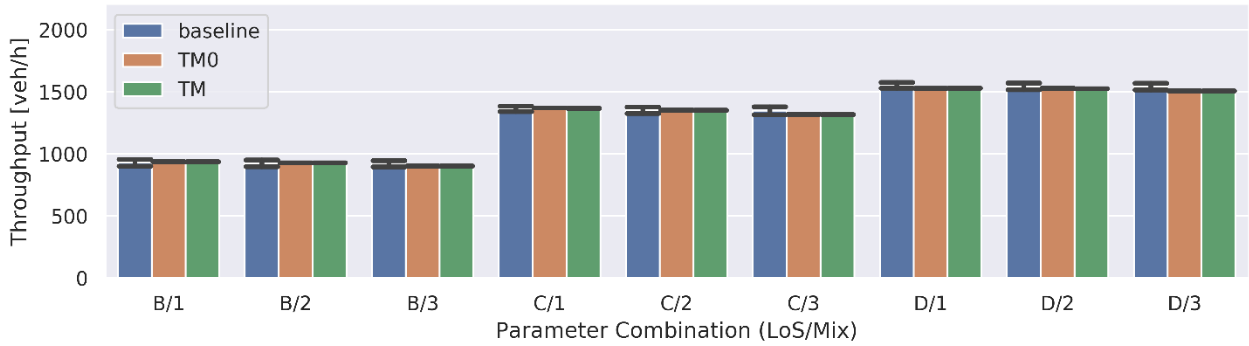


Figure 70: Throughput [veh/h] for use case 2.1 simulation experiments (varying LOS and vehicle mix).

3.2.2.3.3 Impacts on traffic safety

Consistent with the 1st iteration, the KPI: a TTC (time to collision) less than *3 seconds* is used to measure traffic safety, where it is recognised as a critical event.

Network-wide Impacts

Figure 71 shows the average number of TTCs of baseline (blue bar), TM0 (orange bar), and TM (green bar) for three LOS B, C, and D, and for three vehicle mixes 1, 2, and 3.

It is interesting to see that the number of TTCs under scenario TM0 decrease under some parameter combinations, while they increase for others. And the number of TTCs under scenario TM are mostly increasing compared to the baseline and TM0. The former phenomenon can be explained by the parameter of accepted gap in the merging assistant system, in which 1.2 second is considered as an acceptable gap for merging without transition of control. The later phenomenon is expected as the ramp metering stops on-ramp CAVs during red and amber phases (a regular traffic controller is used here since no ramp metering model exists in the current SUMO model). We speculate that the unpredictable sudden break/stop before the ramp metering when it turns red causes a lot of TTC event where in operational situation would not happen.

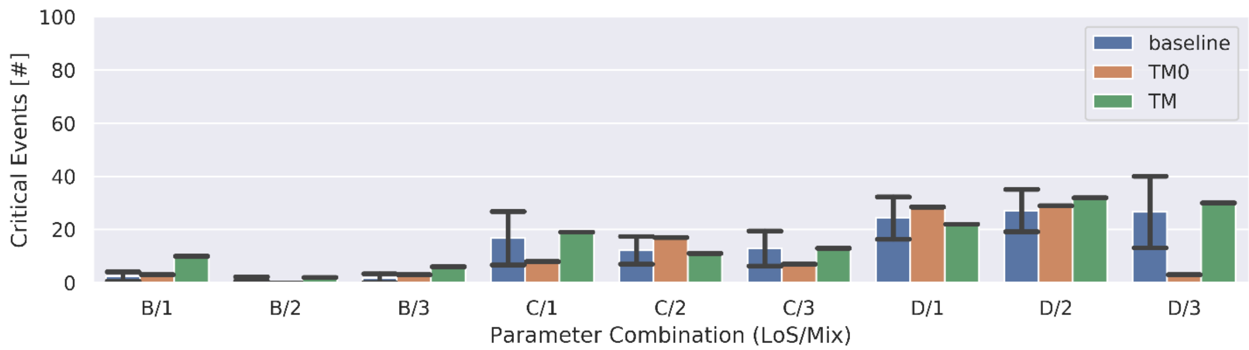


Figure 71: Average number of events with TTCs below 3.0 seconds for use case 2.1 simulation experiments (varying LOS and vehicle mix).

With more investigation in local impact next, we intend to prove the interpretation of TTCs locations.

Local Impacts

Figure 72 shows the TTCs frequency distributions spatially, in accordance to the on-ramp and mainline motorway geographic topology. The darker blue and light blue bar on the x-axis around position 200 (the position of ramp metering) shows the clustering of TTC events, which shows the sudden brake/stop events before ramp metering installation. Another position of TTCs resides in the merging area. Thus, the local impact further confirms our postulation of higher TTCs under TM scenario.

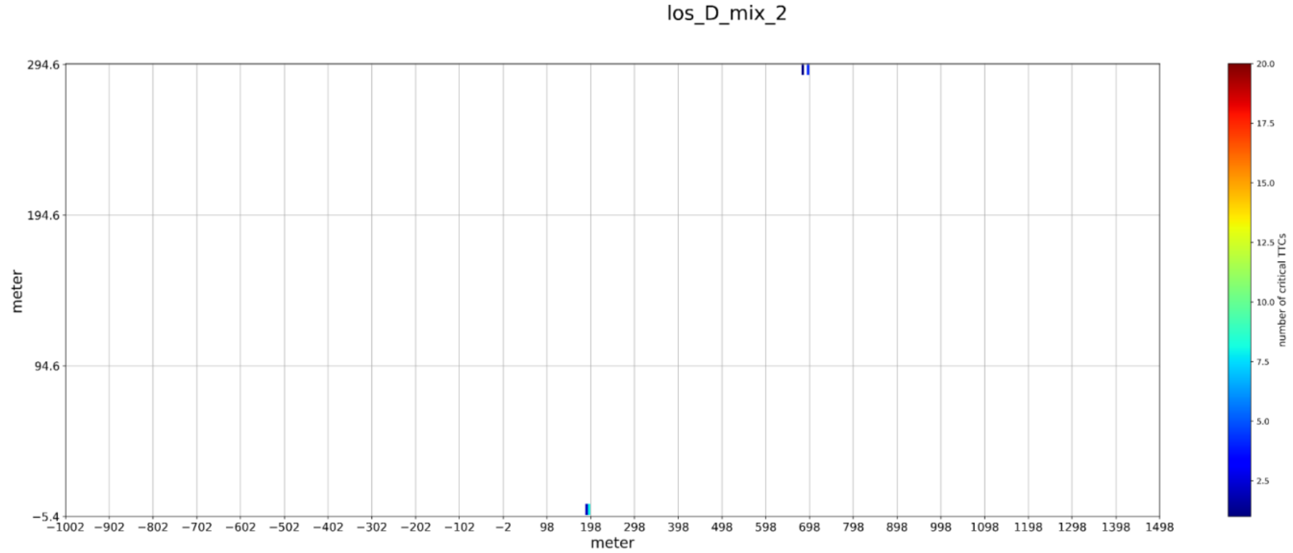


Figure 72: Average number of events with TTCs below 3.0 seconds for use case 2.1 simulation experiments (varying LOS and vehicle mix).

3.2.2.3.4 Environmental impacts

Figure 72 shows the average CO_2 emissions per travelled kilometre of the baseline (blue bar), TM0 (orange bar), and TM (green bar) for LOS B, C, and D, and for three vehicle mixes 1, 2, and 3.

Although it seems inconclusive, subtle decreases can be observed from the scenario baseline to TM0, under different parameter combinations. The slight increase from TM0 to TM could be caused by the aforementioned sudden stops in front of the ramp metering. The variation of CO_2 emissions are consistently decreasing from the baseline to TM0 or TM scenarios, which are interpreted in the traffic dynamic impact section as well.

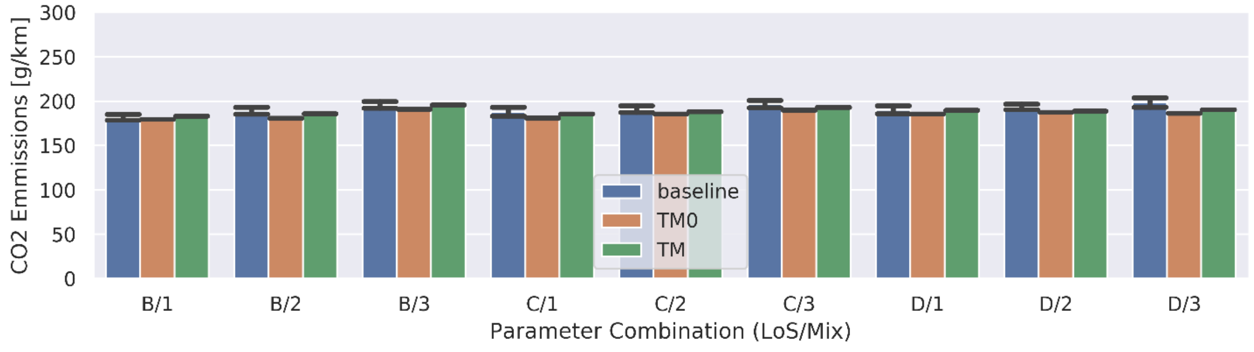


Figure 73: CO_2 emissions [g/km] for use case 2.1 simulation experiments (varying LOS and vehicle mix).

3.2.2.3.5 Metrics for Control Transitions

The metrics for control transitions are plotted in Figure 74 with CAVs' ToC percentages for UC 2.1, for the baseline (blue bar), TM0 (red bar), and TM (green bar), under each parameter combination, note that the plot used seed 1042 instead of all 10 seeds.

Significant decreases of the ToC percentages can be observed for TM0 and TM compared to baseline. Under the baseline scenario, around 85% of the on-ramp CAVs would perform a transition of control to complete motorway merging manoeuvers. This KPI decreases to around 5% under the control logic of merging assistant system and further decreases to around 1% under the ramp metering control.

The significant improvement proves the function capability of the merging assistant system and ramp metering, in the aspect of preventing ToC/MRM and assist CAVs during motorway merging in a complex mixed traffic situation.

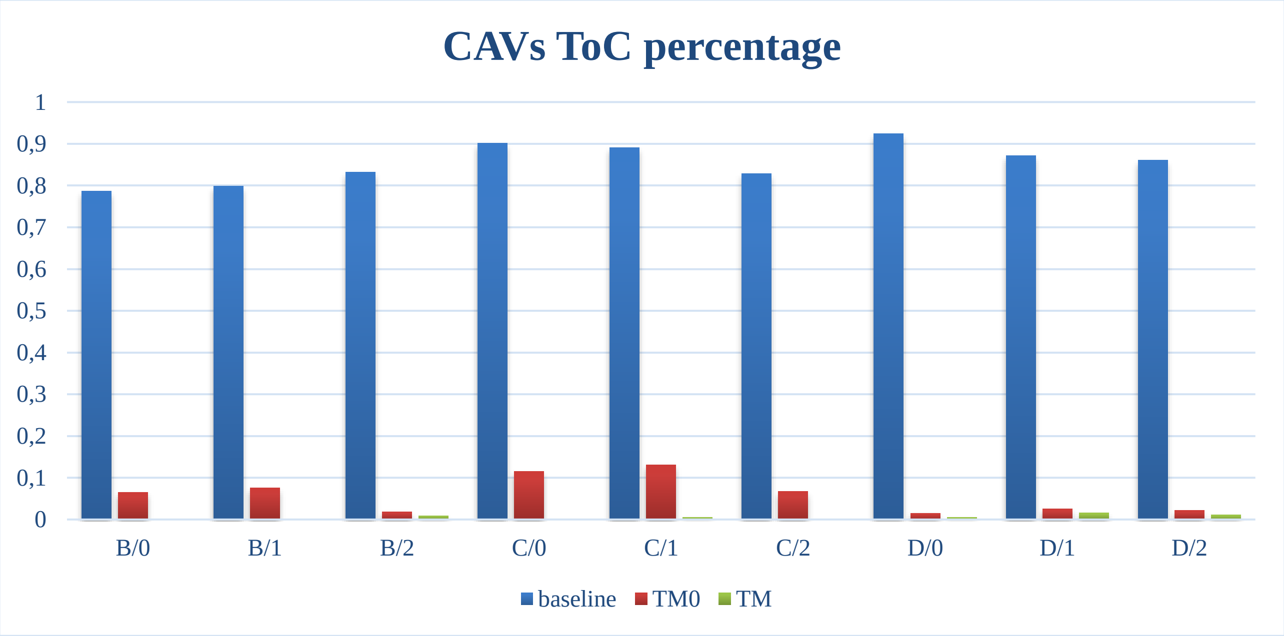


Figure 74: CAVs ToC percentage for use case 2.1 simulation experiments (varying LOS and vehicle mix).

3.2.2.4 Discussion

The previous section showed the most representative KPI plots of the simulation results after introducing an additional component – ramp metering (using the merging assistant system algorithm). The major improvements on the ToC percentage were achieved with the logic of gap searching, speed advice, and gap creation via pairing.

The other positive result is in the traffic dynamics, as the number of lane changes also decreased under the control logic as well as the variations between runs. Less variations from the baseline to TM0 and TM can be observed in almost all KPIs (except TTCs). It shows the improvement on homogeneity of traffic flow.

The slightly negative impact of traffic efficiency and environmental impact could correlate to the parameter settings of the merging assistant system and ramp metering configuration. The control logic has strengthened safety objectives as one would expect. The TA + MRM zones are solely preserved for ToC and MRM. This is controlled via law- enforced ramp metering installation.

Therefore, less late merging and no end-of-the-acceleration-lane merging will happen, which could cost the performance of average travel time and average network speed, especially under heavier traffic demand due to lower capacity of the on-ramp.

The significant increase on TTCs events and the clusters before ramp metering can be improved via parameter tuning in the merging assistant system and ramp metering. For future research, these parameters can be better experimented in order to reduce these inaccurate behaviours of CAVs encountering a ramp metering installation. The merging assistant system and ramp metering models are still under development, which need further investigations and debugging to be exceptions-free. More local results plotting can also help to produce more conclusive results comparison.

Additionally, the CACC model under the influence of speed advice is another aspect that needs further study, as we observe inconsistency in speed advice following, which can be crucial for car following and lane changing manoeuvres, especially under time critical, high speed motorway situations.

In conclusion, the merging assistant system and the intelligent ramp metering using this system shows the functional ability to prevent ToC and MRM. The trade-off between efficiency and ToC percentage is as expected for non-congested traffic situations. For congested traffic situations, ramp metering targeting lower ToC rates is not effective anymore because of expected increasing ToCs and MRMs of merging vehicles.

3.2.3 Scenario 2 (Use case 2.3): Intersection handling due to incident

3.2.3.1 Introduction

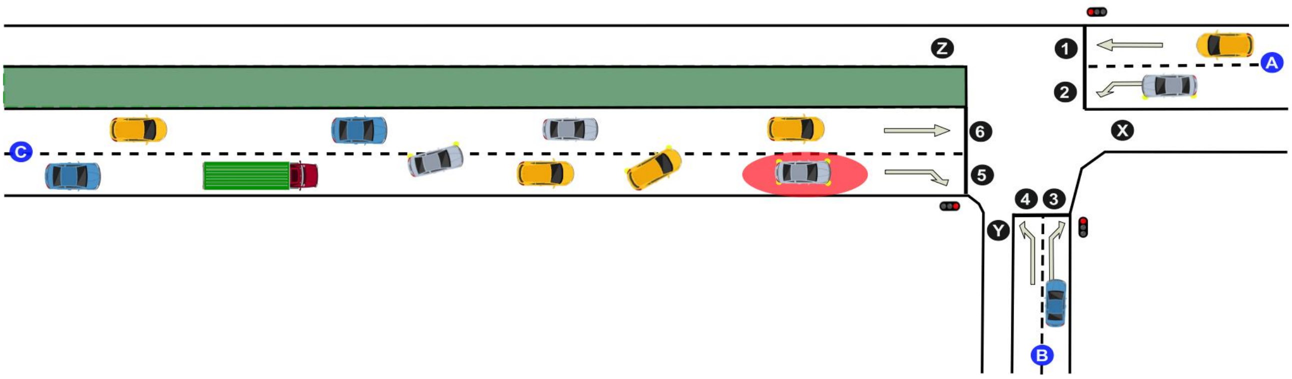


Figure 75: Scenario layout of use case 2.3.

Figure 75 gives a high-level schematic overview of the use case. An incident occurs just before the stop line of the right turning traffic lane on the west approach (approach C, lane 5). The incident is blocking lane 5 approximately 35 meters before the stop line and therefore vehicles driving on this lane will need to use the through traffic lane (approach C, lane 6) to drive around the incident. In the baseline scenario, see paragraph 4.2.3 of Deliverable D3.1, the RSI of the TLC will be informed about the incident on lane 5 and shares its relevant information with the approaching CAVs/CVs. The warning information and location is shared via DENM. Depending on whether the (C)AV can recognise the situation, either a ToR is issued which ends up in a ToC or an MRM, or the (C)AV recognises the situation. In both cases, automated and manually driven vehicles will try to merge into lane 6 to overcome the incident. A portion of the vehicles in automated mode which do not know how to turn right safely are assumed to continue their journey towards lane *x* and find a new route. Manually driven vehicles and another portion of the vehicles driving in automated mode are assumed to turn right at the junction.

3.2.3.2 Traffic management setup

After the RSI detects an incident, traffic managers will firstly try to create a safe situation on the incident location. This is done by broadcasting the incident information to approaching vehicles, close the lane on the incident location, and set a temporary speed limit around the incident zone. To be able to guide automated vehicles alongside the incident and to make the right turn possible again for all the traffic the lanes, usage of lane 5 and 6 are altered and the timing plan is changed to make right turns from lane 6 possible. This information is then relayed to the approaching vehicles. Therefore, CAVs and CVs:

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

3.2.3.2.1 Traffic management logic

Figure 76 shows the steps taken when an incident occurs in front of the traffic light controller and how a roll back is done in case the incident is resolved.

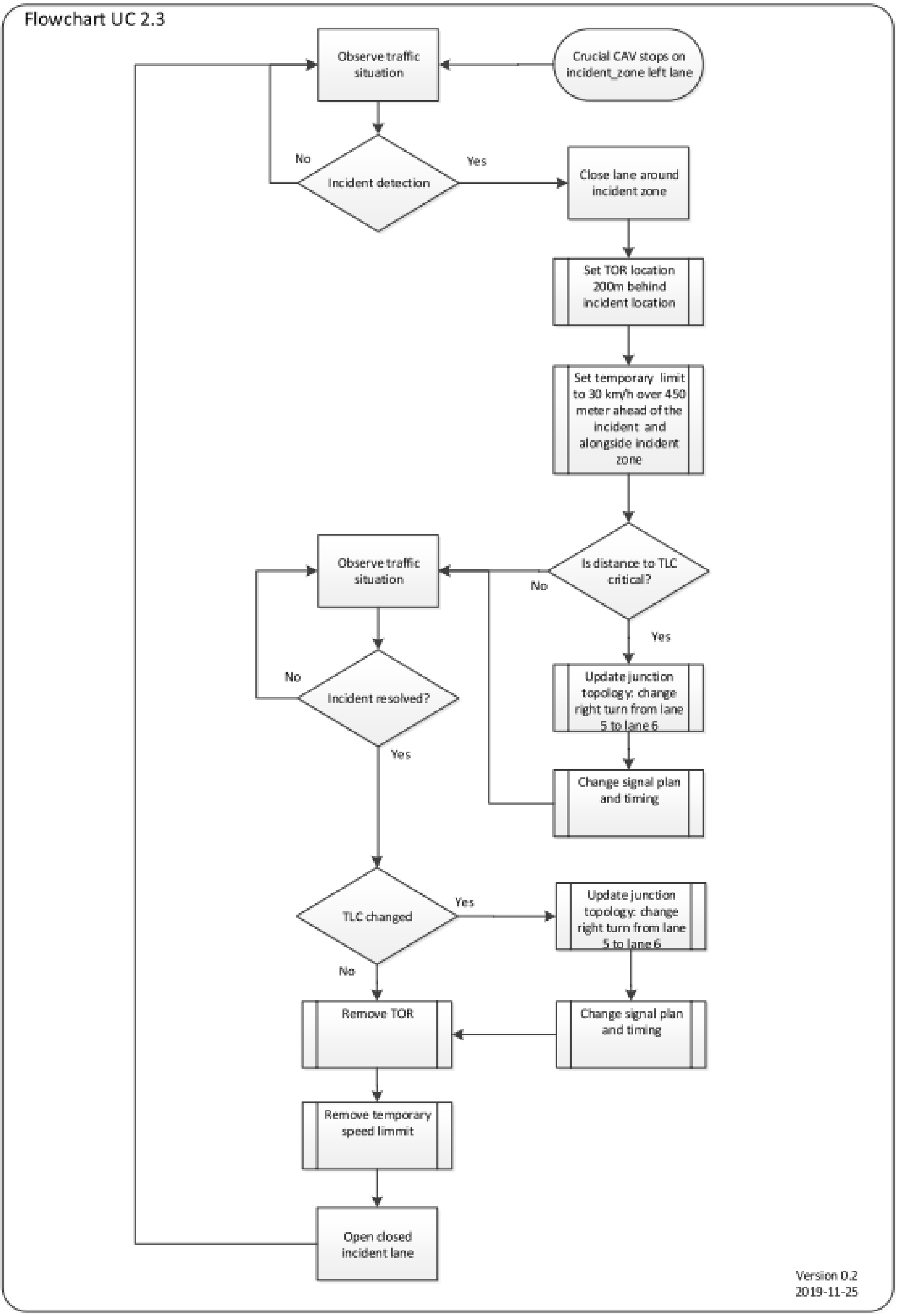


Figure 76: Flow chart of traffic management operations for use case 2.3.

On reception of the alert message from the incident, the RSI will start to implement the traffic management measures as described in Table 16. Due to the specific use case implementation, all CAVs are able to make the right turn in a safe way and will not continue straight as in the baseline scenario.

Table 16: Traffic management measures scenario 2 (use case 2.3).

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

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

Please note that AVs and LVs will not receive any information. Therefore, ToCs will occur for AVs in the same way as in the baseline situation.

3.2.3.2.2 Baseline scenario adaptation

The baseline simulations showed that the percentage of CAVs increases throughput at LOS B and C but disrupts it at LOS D. Therefore, at lower intensities the traffic flow is better with higher percentages of CAVs, but when the traffic density increases to LOS D the impact is reversed.

In the baseline simulations we assumed that 50% the CAVs do not know how to turn right safely and continued their journey straight ahead and find a new route. In the traffic management scenario these vehicles will be able to turn right safely at the junction.

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

3.2.3.3 Results

3.2.3.3.1 Impacts on traffic efficiency

Figure 77 shows the travel time for Day 1 C-ITS (DO) measurements (blue bar) and the traffic management (TM) implementation (orange bar) for three LOS B, C, and D, and for three vehicle mixes 1, 2, and 3. This KPI provides a comparison of traffic efficiency on the whole network among these two scenarios with a different degree of traffic management intensity.

The travel time for the traffic management scenario is for LOS B comparable with DO. Here is a temporary speed reduction (50 km/h to 30 km/h) nearby the incident location. But due to a larger portion of green time for movement 5+6, the average speed performs just a bit better in the traffic management scenario. Looking at LOS C the travel time of the DO is as expected due to an increasing traffic demand in combination with a bigger portion of CAVs in the network (mixes 2 and 3). As observed in the baseline simulations (see Deliverable D3.1), due to greater distances CAVs use to drive safely or change lanes safely, we observe an increasing drop of speed. Looking at the results for LOS C with traffic management, the travel time is still more or less the same. Only at LOS D the travel times for the traffic management scenario start to increase. The better performance of the traffic management scenario is due to a 10% extra green time of the TLC and maybe some harmonisation because of the reduced speeds. This can be analysed when looking at the local impacts. In addition, we observe how the travel time increases from LOS C to LOS D, but that in comparison with the baseline scenario it is still significantly less.

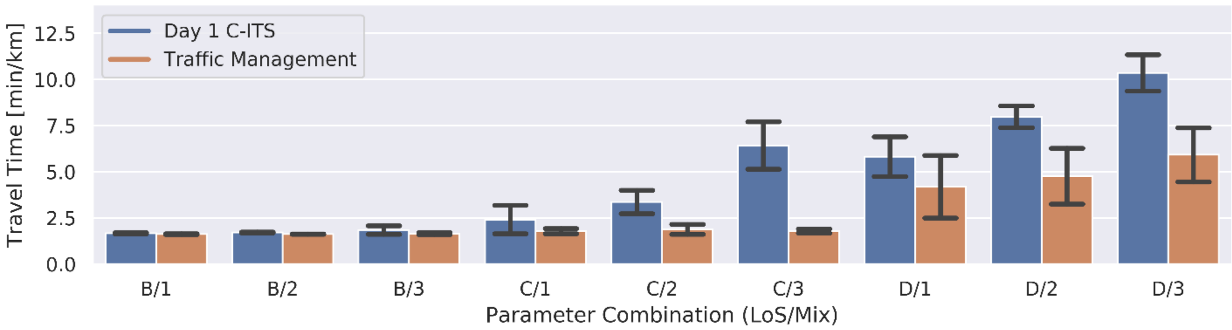


Figure 77: Travel time [min/km] for use case 2.3 simulation experiments (varying LOS and vehicle mix).

Local impacts

Figure 78 shows the flow diagrams, as an example, for the DO and TM scenario for LOS C Mix 3. In the DO a queue starts to form behind the incident and after 20 minutes spills back upstream towards the start of the network. As a result, the traffic input into the network is reduced because of slow driving vehicles on the first edge of the network. In the traffic management scenario a queue builds up behind the incident. Due to a reduced speed and extra green time for signal group 5+6 the queue now and then is resolved and appears again, but the network still has a good performance.

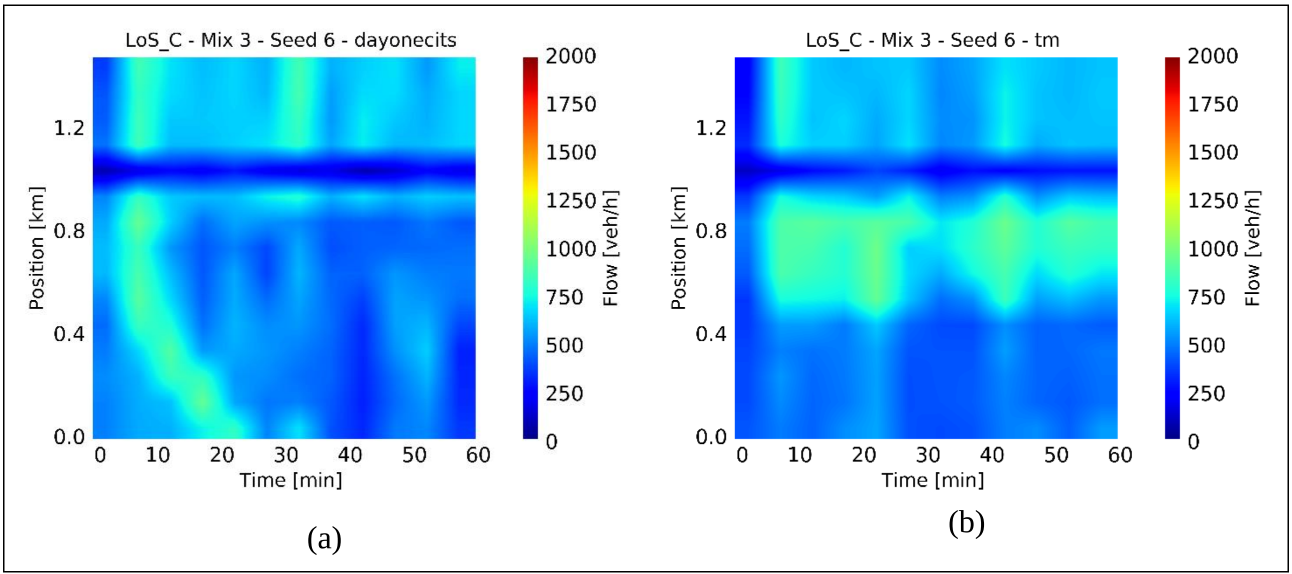


Figure 78: Exemplary time-space-diagrams for Day-1 C-ITS LOS C – vehicle mix 3 (seed 6) Day 1 C-ITS (left column a) and TM (right column b) for use case 2.3.

As discussed above in the DO scenario the traffic jam is really severe in the simulation of LOS D for all seeds. The traffic management scenario preforms significantly better due to the measures taken, up half of the travel time of the DO scenario with LOS D mix 3. Figure 79 shows the spill back of the queue within 18 minutes back to the starting point of the network which has the effect that less vehicles can enter the network and will exit the simulation network much later in time. For the traffic management scenario there is also a queue building up, but the spill back will hit the starting point of the simulation network just at the end of the analysed period.

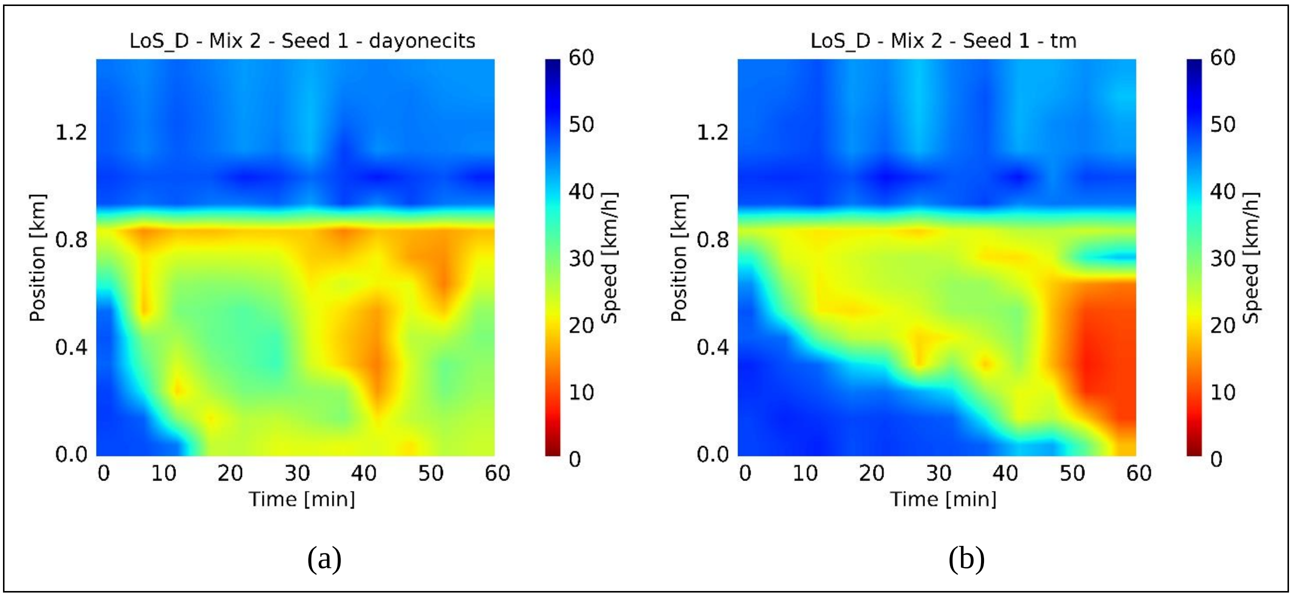


Figure 79: Exemplary time-space-diagrams for Day 1 C-ITS LOS D – vehicle mix 1 (seed 1) measured speed dayone-CITS (left column a) and TM (right column b) for use case 2.3.

3.2.3.3.2 Impacts on traffic dynamics

Figure 80 shows the total throughput of the different simulations. Both scenarios show the same level of throughput, with only the throughput of the traffic management scenario for LOS C and

LOS D being just a bit better than the DO scenario. The closure of a complete lane near the junction, all the way op to the stop line, will disrupt the throughput of traffic. As a counter measure signal group 5 gets 10 seconds extra green. This results in a comparable throughput for both scenarios.

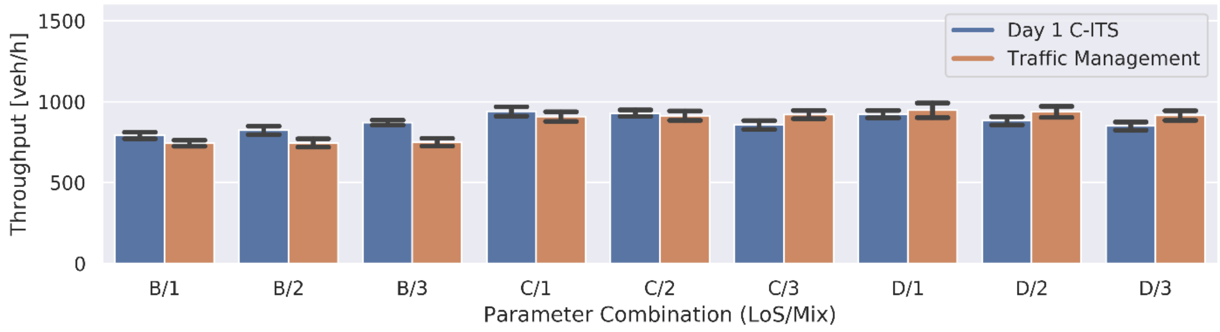


Figure 80: Throughput [veh/h] for use case 2.3 simulation experiments (varying LOS and vehicle mix).

As Figure 81 shows, for the number of lanes changes per travelled kilometre the traffic management scenario has a lower amount of changes. This effect has a twofold explanation. Firstly, due to the lane closure of lane 5 CAVs know when approaching the incident they have to use lane 6 to make a right turn and will try to get into lane 6 and will stay in this lane. From observation of the DO scenario more vehicles preform a lane change form lane 6 to lane 5 because lane 5 is rather empty but then the incident is detected by the CAV or driver and vehicles change back to lane 6. Secondly, since the traffic management scenario has less congestion vehicles will make less lane changes form lane 6 to 5 and back again to pass the queue on lane 6 because this queue is less severe.

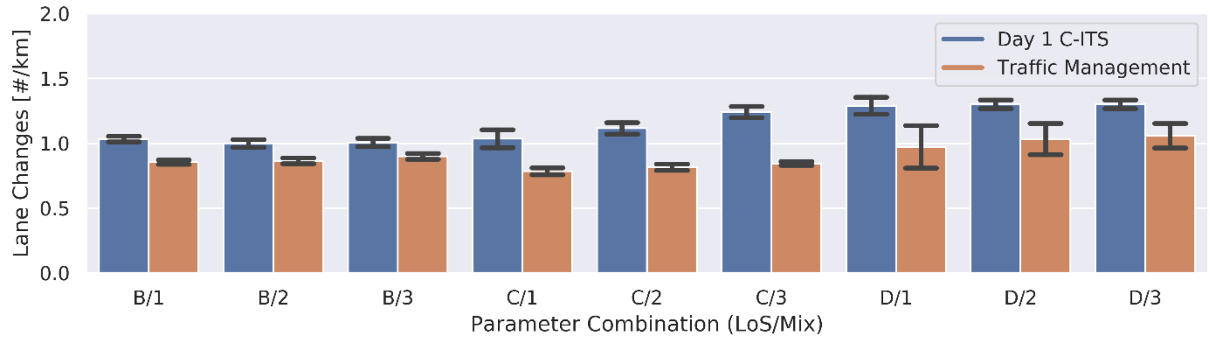


Figure 81: Number of lane changes per kilometre [#/km] for use case 2.3 simulation experiments (varying LOS and vehicle mix).

3.2.3.3.3 Impacts on traffic safety

When looking at Figure 82, the pattern of critical events follows the pattern of increasing travel times as shown in Figure 77 which is a measure of the development of queues and stop-and-go traffic in the network what is in line with what can be expected in the simulated scenarios. For the traffic management scenario simulation of LOS D a bigger spread in results over the different seeds (black bar plotted over the bar) is observed. An explanation can be that the saturation of the network is reached in some seeds and in other seeds not yet, which as an effect gives a bigger spread between the different seeds (see also Figure 83). The same pattern can be observed for the DO scenario with LOS C.

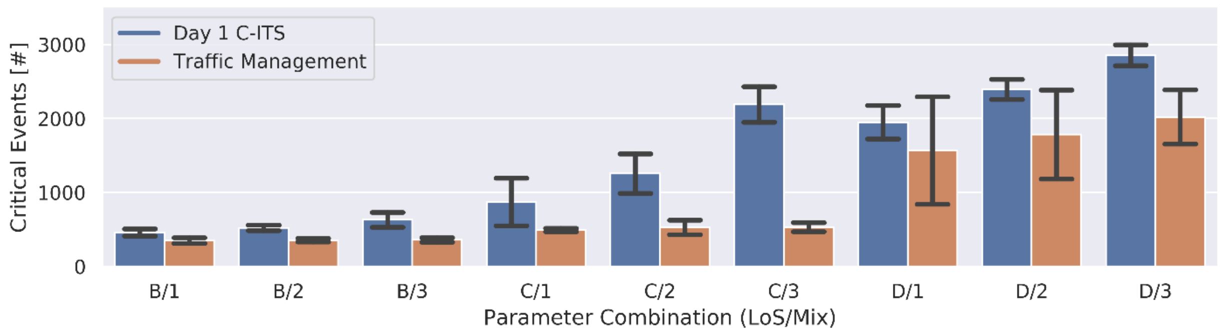


Figure 82: Average number of events with TTCs below 3.0 seconds for use case 2.3 simulation experiments (varying LOS and vehicle mix).

Local Impacts

Regarding the big spread in the TTCs for the TM scenario as mentioned before. Figure 83 shows the TTC distribution of the TM scenario for LOS C mix 1. Seeds 1, 3, 6, and 7 show a limited number of TTC while the other seeds show an increasing number.

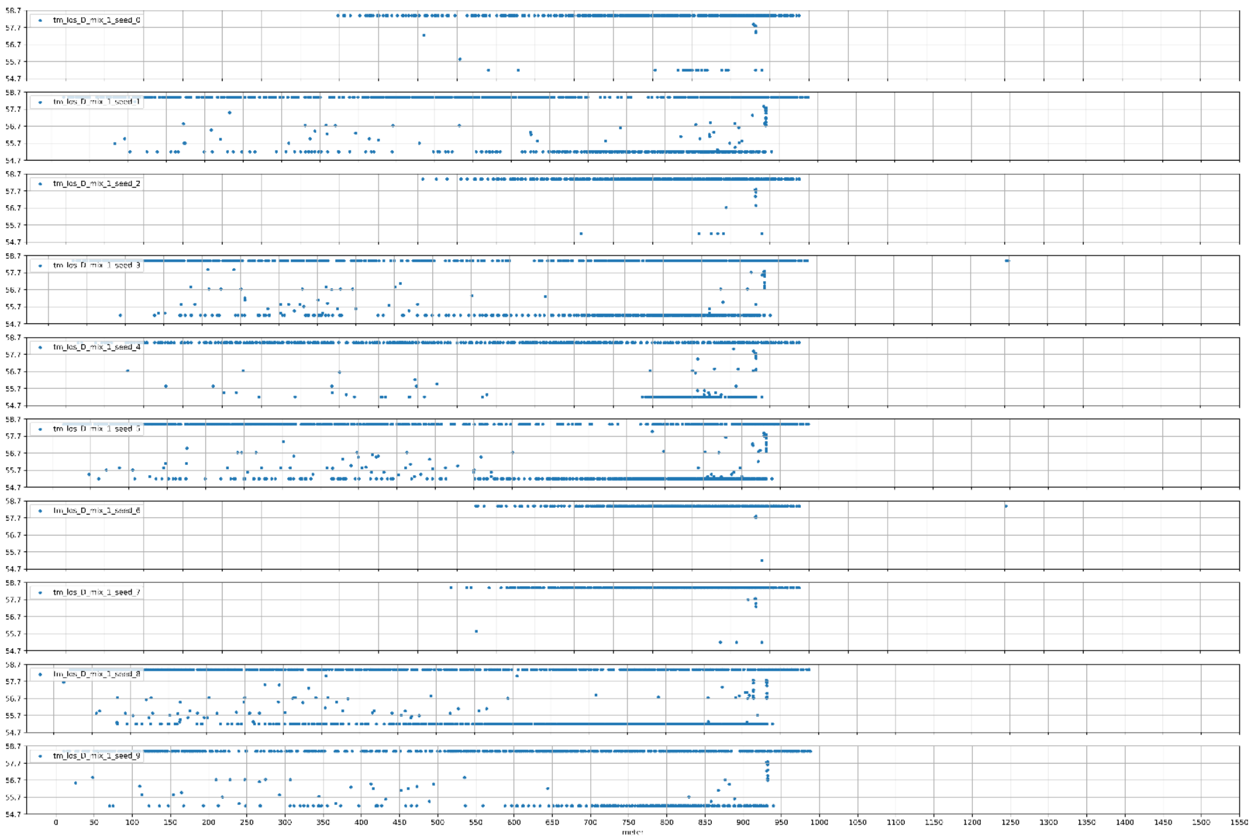
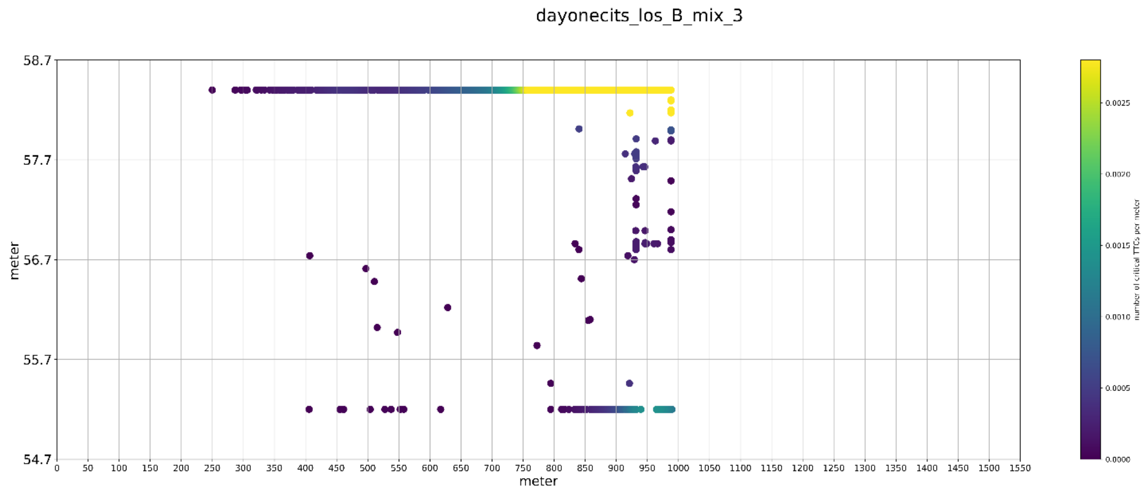


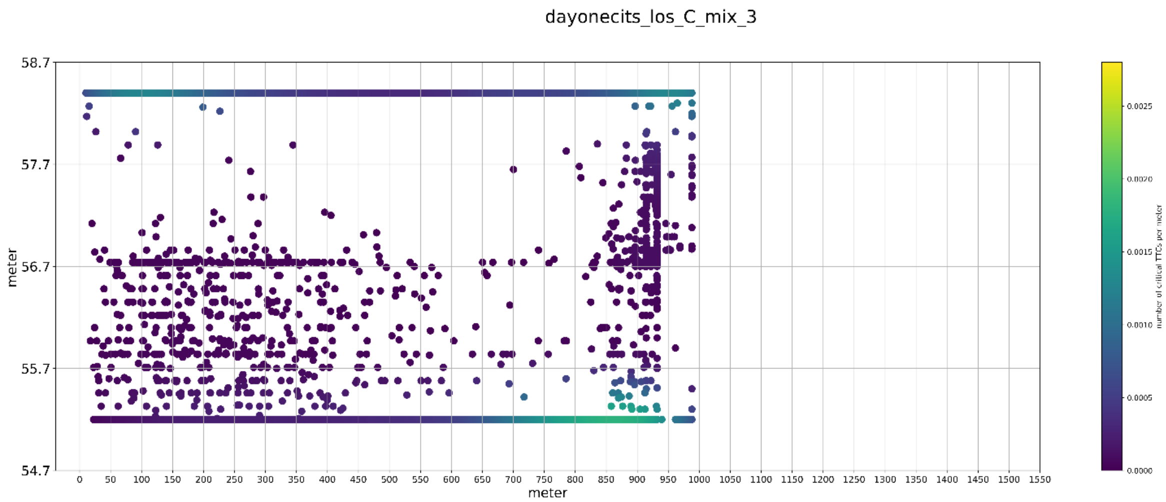
Figure 83: Spatial distribution of critical TTCs (< 3 sec) scenario TM, for use case 2.3 simulation experiments (LOS C and vehicle mix 1).

The TTC density plots feature the aggregated number of critical TTCs of 10 seeds (per LOS/mix) marked as bins along the network. Each plotted bin means that at least one TTC occurred at this position. The colour of a bin then indicates the amount of TTCs at this marked position. So, when, e.g., several TTCs concentrate within a certain area, the colours translate as a spatial density for interpretation of the TTC distribution.

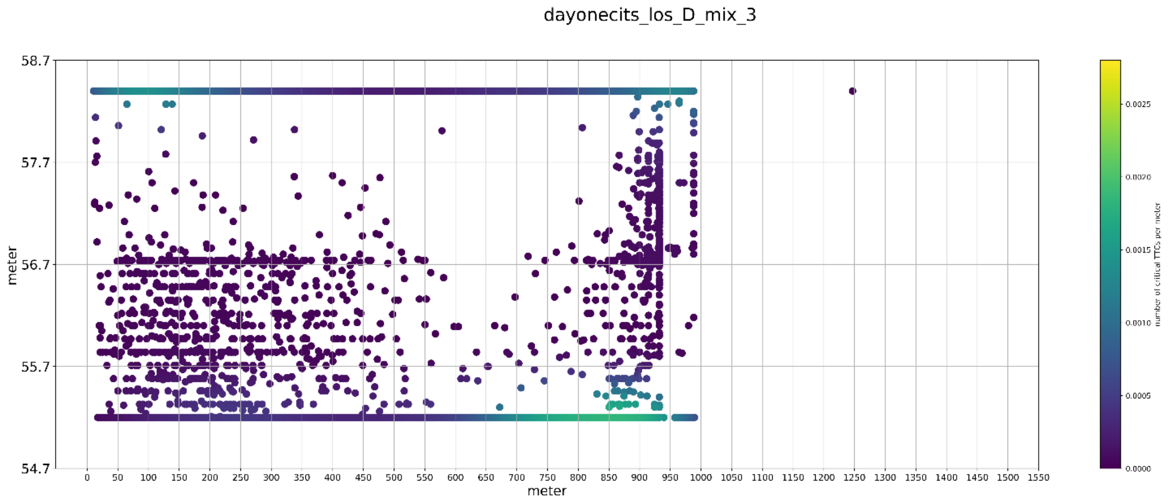
Looking into the DO-scenario, see Figure 84, at LOS B the TTCs are dense on the left lane just nearby the incident (at 950 m) up until the signal head. When traffic demand is increased, the TTCs are spread more and more backwards into the network and are more concentrated on the right lane. Looking at the aforementioned figure of mix 3 with LOS C and D, TTCs during lane changes occur mostly between 50 and 500 meters and directly behind the incident. This distribution occurs due to the build-up of the queue mainly on lane 6 and vehicles trying to merge from lane 5 into the traffic queue.



(a)



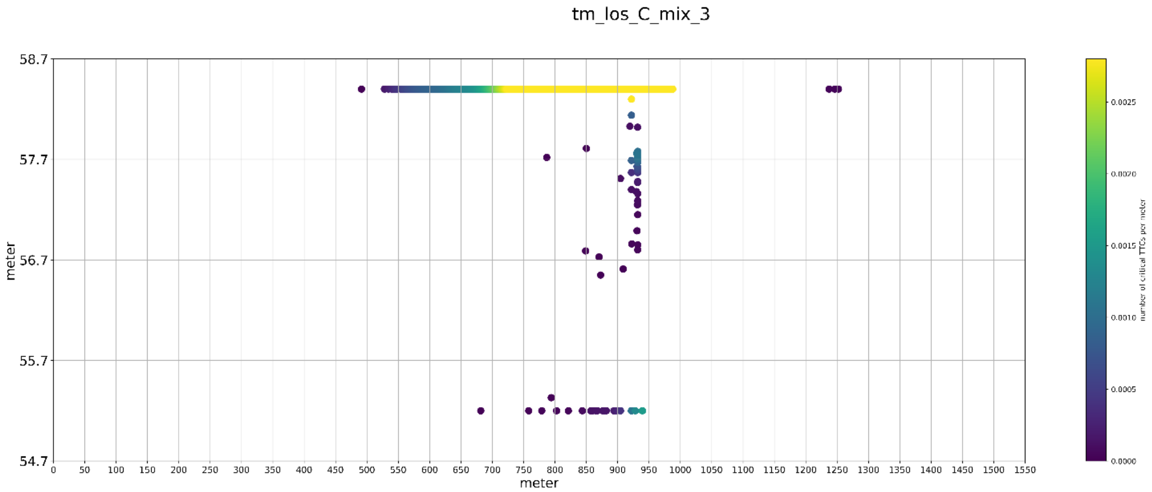
(b)



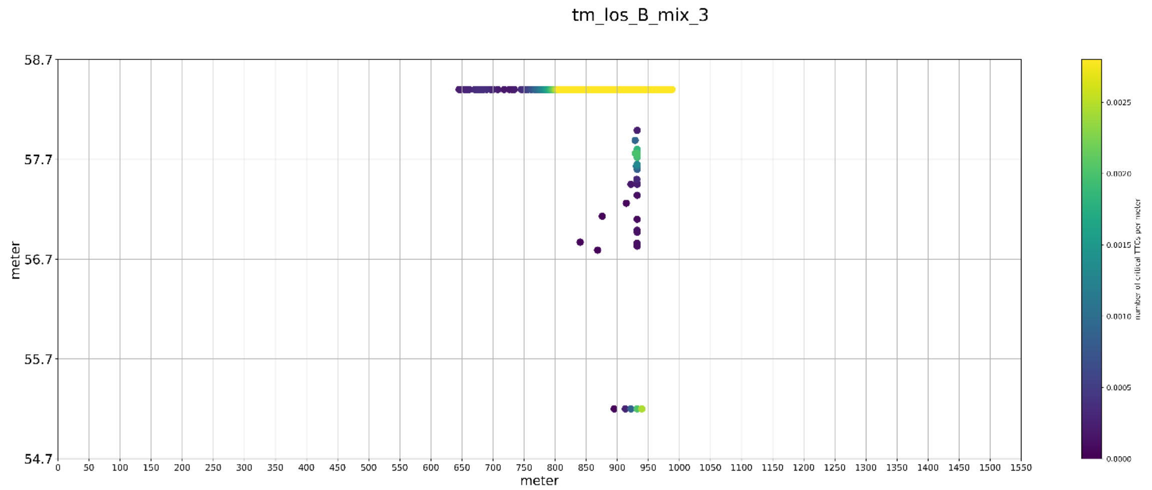
(c)

Figure 84: Spatial distribution of critical TTCs (< 3 sec) scenario DO, for use case 2.3 simulation experiments (varying LOS and vehicle mix 3).

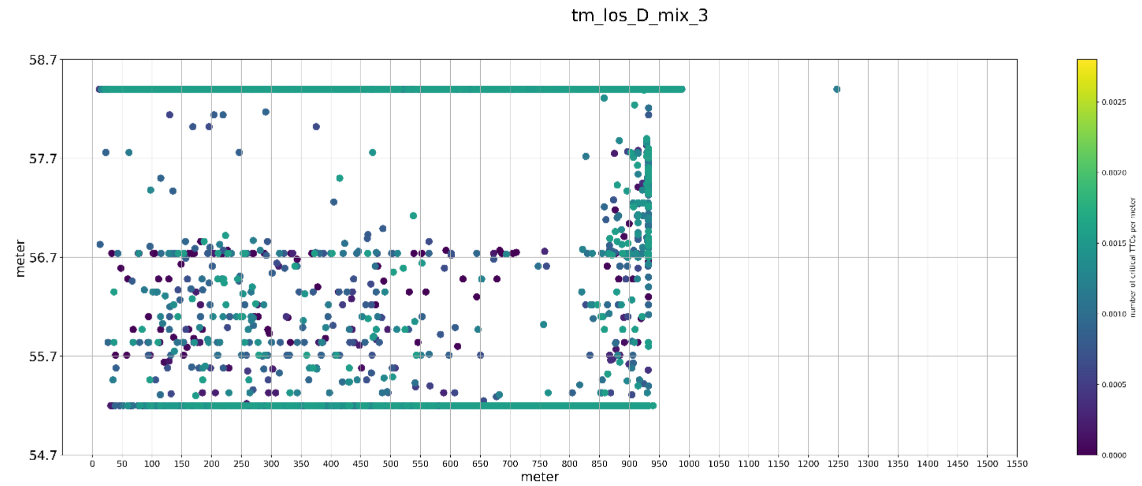
Figure 85 shows the TTC distribution of the traffic management scenario. The pattern is the same taking into account the different saturation in the traffic management scenario. Figure (c) shows a denser coloured TTC plot due to the higher occurrence rate on the same location. There is no obvious reason why this ocurs. Due to the lane closure around the incident the figures show no TTC in front of the incident on the right lane.



(a)



(b)



(c)

Figure 85: Spatial distribution of critical TTCs (< 3 sec) scenario TM, for use case 2.3 simulation experiments (varying LOS and vehicle mix).

3.2.3.3.4 Environmental impacts

CO_2 is selected as the indicator for investigating the environmental impacts of mixed traffic and control transitions in the context of scenario 2.3. Figure 86 shows the average CO_2 emissions per travelled kilometre for the different vehicle mixes.

For the traffic management scenario the level of CO_2 emissions remains roughly the same for all mixes at LOS B (free flow traffic conditions). On the other hand, traffic management yields significant CO_2 emissions savings for increased share of CVs/CAVs in the fleet mix (Mix 2/Mix 3) and LOS C. For LOS D the CO_2 levels follow the line of the ascending travel time in the network and the differences between Day 1 C-ITS and Traffic Management Scenarios are not statistically significant. As mentioned with the TTC distribution for LOS D we encounter a bigger spread because the simulation, depending on the seed, hits the saturation level of the network which can gives more stop and go traffic, lane changes, and merging traffic.

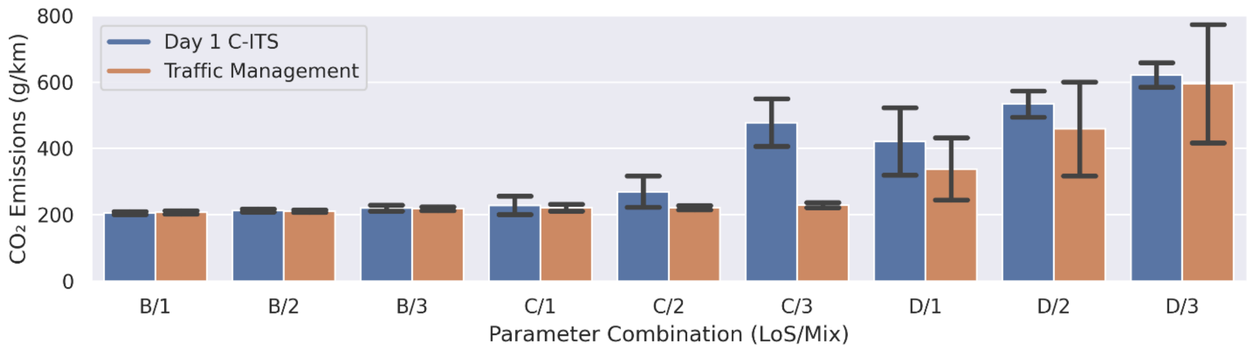


Figure 86: CO_2 emissions [g/km] for use case 2.3 simulation experiments (varying LOS and vehicle mix).

3.2.3.4 Discussion

In the traffic management scenario, CAVs and CVs receive information about the incident itself (position, type, etc.), as well as a reduced speed advice, and are able to use lane 6 (straight through) to turn right. Due to an updated timing plan where the traffic coming from the incident road gets extra green time (92 seconds instead of 82 seconds), the saturation and travel times in the traffic management scenario are up until LOS D. In the LOS D simulations, the buildup of the queue is more persistent. The impact of the incident is nevertheless less severe in comparison to the Day 1 C-ITS simulations.

Any effects of the speed reduction (50 km/h to 30 km/h) in the traffic management scenario nearby the incident location cannot be distilled from the simulation results. There can be an impact on at bit smoother traffic flow and or less TTCs near the incident, but that comparison cannot be made with the existing results.

3.2.4 Scenario 4 (Use case 4.2): Safe spot in lane of blockage & Lane change Assistant

3.2.4.1 Introduction

Work zones are expected to disrupt vehicle automation by inducing vehicle disengagements. Ambiguous lane markings and complex traffic situations (e.g., merging) can be challenging for CAVs, and result in system-initiated ToCs from the CAV side. Day 1 C-ITS applications can proactively warn C(A)Vs about an imminent work zone. In this case, C(A)Vs that cannot cope with work zones in automated mode will issue take-over requests (TOR) when DENM messages are received and the vehicle operator is expected to take-over control and manually drive the C(A)V past the work zone (until a higher level of automation is feasible again).

However, drivers of CAVs might be involved in secondary driving tasks and fail to respond in a timely manner (within the available time budget) to TORs. Thus, CAVs will execute MRM to bring the vehicle to a full stop until the driver regains control. Unless these MRMs are guided to safe spots upstream of work zones (see Figure 87), their negative impacts on safety and traffic efficiency are expected to be significant. The TMC can be informed about the CAV status (location and speed, driving mode, and ToC status) using V2I communications and intervene when an MRM becomes foreseeable to provide guidance to the CAV towards predefined safe spots. TMC instructions could encompass both longitudinal and lateral guidance to safe spots. We assume that CAVs will be capable of lane changing during MRMs.

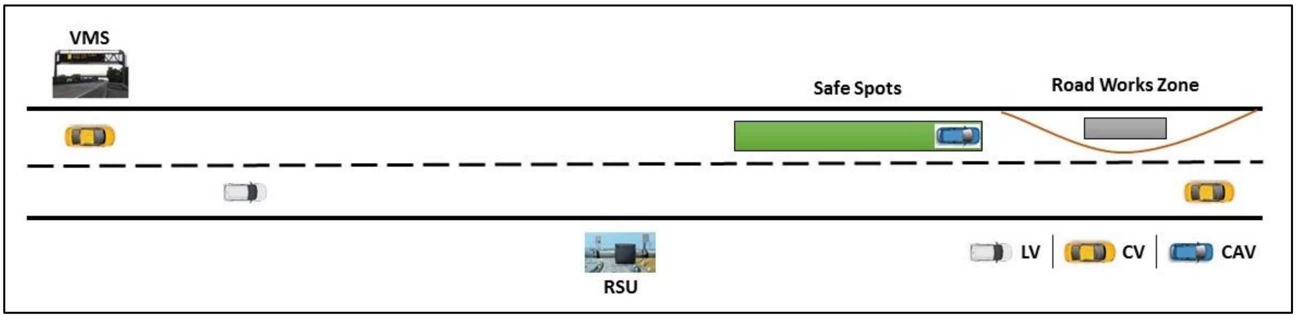


Figure 87: Safe spots upstream of road works zone.

On the other hand, few CAVs (highly automated) might be able to pass the work zone in automated mode if they are driving on the non-blocked lane(s) and thus they will not issue a TOR upon a DENM reception. Nonetheless, if the latter CAVs drive on the blocked lane(s) and cannot merge unimpeded on the non-blocked lane(s) due to surrounding traffic, the automation will dynamically issue TOR that can significantly disrupt traffic operations in the proximity of the work zone. Hence, the TMC can provide lane change advice to CAVs (highly automated) when they enter the RSU's communication range (i.e. change lane driving on blocked lane(s) or keep lane if driving on non-blocked lane(s)). Moreover, cooperative driving can take place to facilitate cooperative lane changes towards the non-blocked lane(s) if prevailing conditions are favourable.

***Note:** *We assume that CV drivers will always remain in the loop and take-over vehicle control when TORs are issued due to DENM reception.*

3.2.4.2 Traffic management setup

3.2.4.2.1 Baseline scenario adaptation

In the second project iteration, no adaptations to the baseline scenarios presented in Deliverable D3.1 (Mintsis et. al., 2019) were required in the context of Deliverable D4.2. However, note that the baseline for Scenario 4.2 in the second project iteration has been adapted in contrast to the first project iteration. While in the first project iteration CAVs issued TORs when work zone traffic signs entered their sensor range, in the second iteration we assumed the existence of Day 1 C-ITS applications that proactively warn CAVs (in range) about imminent work zones. Therefore, TORs are issued at the time of DENM message reception. More detailed information regarding the baseline of Scenario 4.2 in the second project iteration can be found in Deliverable D3.1 (Mintsis et. al., 2019).

3.2.4.2.2 Traffic management logic

The control logic of TransAID Service 4 is presented in Figure 88.

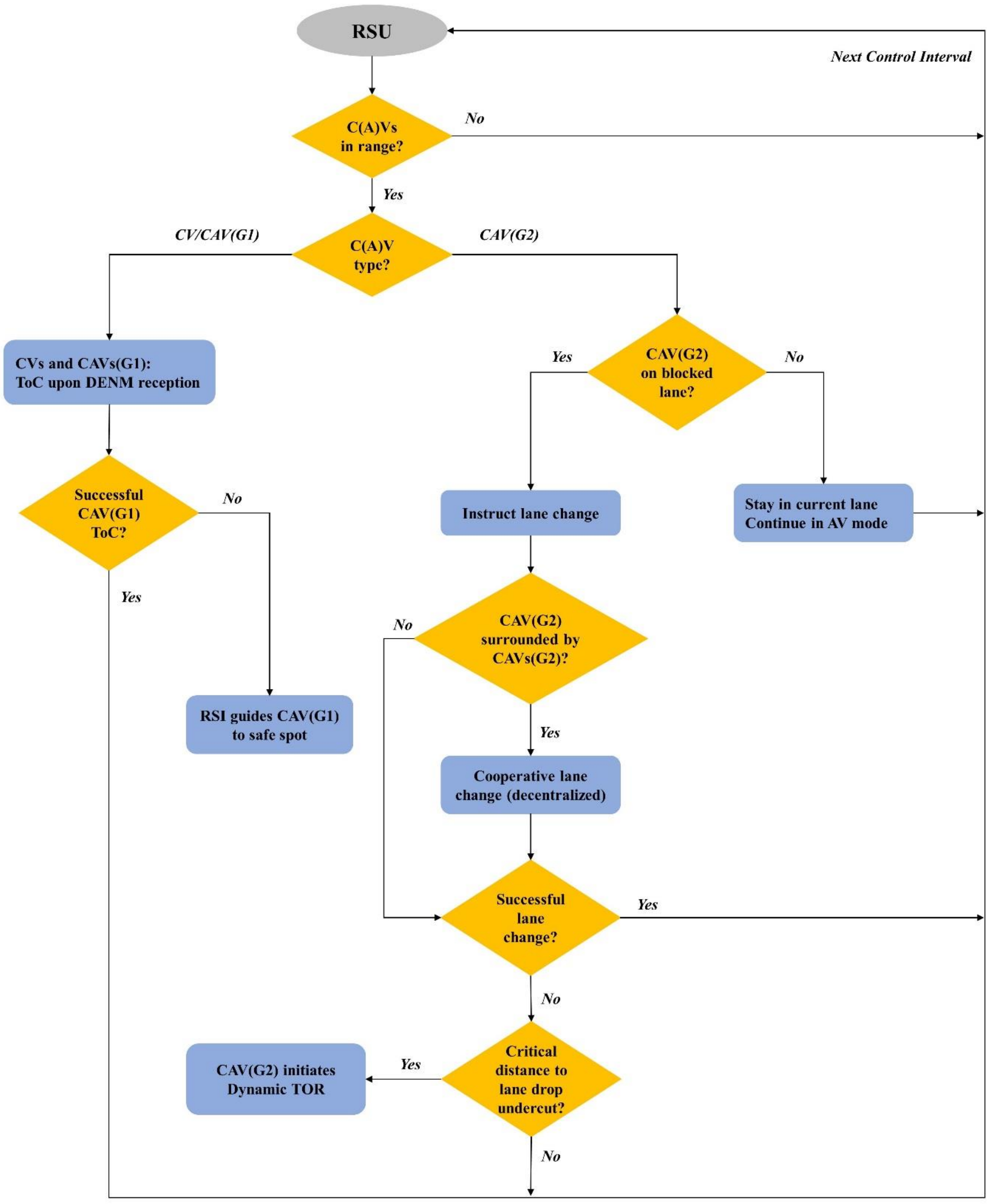


Figure 88: Control logic of TransAID Service 4 (2nd project iteration).

C(A)Vs enter the communication range and receive DENM and MAPEM messages regarding the imminent work zone. Moreover, the RSI receives information about CAVs (location, dynamics, type, etc.) via CAM messages transmitted by CAVs. CVs issue system-initiated TORs upon DENM and MAPEM reception, which always result in successful ToCs in the context of our simulation experiments.

CAVs are divided into two groups based on their capabilities to accommodate work zone scenarios. CAVs belonging to the first group (G1) cannot cope with work zones in automated mode, and thus issue TORs upon DENM and MAPEM reception. f drivers fail to respond to the latter TORs, CAVs use the MAMEP information (containing the safe spot location) to drive towards the safe stop.

CAVs belonging to the second group can pass work zones in automated mode if they travel on the non-blocked lane(s) or can merge unimpeded (from surrounding traffic) to non-blocked lane(s). Otherwise, they issue dynamic TORs in the close proximity of the work zone. Hence, the RSI provides lane change advice to CAVs (G2) when they enter communication range to prevent dynamic TORs that inherently exhibit limited available lead time. In the case CAVs (G2) drive on the open lane, the RSI instructs lane keeping, while in the opposite occasion the RSI instructs lane changing. If CAVs (G2) are surrounded by other CAVs (G2) cooperative lane changing is also possible based on the distributed approach presented in Deliverable D3.2 (Mintsis et al., 2018).

According to the aforementioned description of Scenario 4.2, cooperative driving is feasible in the traffic management scenario. However, in the cooperative driving era digital infrastructure is expected to be more widespread. Thus, we assume that two RSUs are available in the motorway case in order to examine the effects of increased communication range. RSU1 is located 300 m upstream of the work zone, while RSU2 is located 900 m upstream of the work zone (see Figure 89).

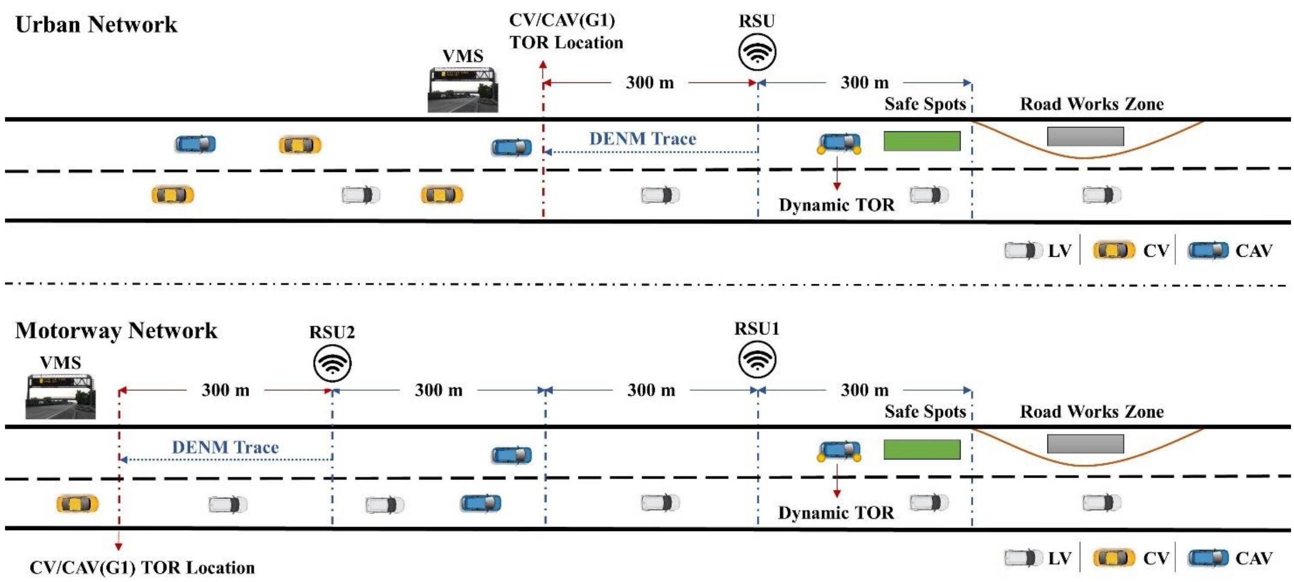


Figure 89: RSU locations for urban and motorway networks.

The addition of an extra RSU in the traffic management scenario required adaptation in the motorway network configuration to ensure there is available roadway space to be covered by both RSUs. Thus, the approaching area's length was increased to 1500 m and the insertion area's length was reduced to 300 m (see Table 17). The total communication range extends to 1200 m along the approaching area.

Table 17: Network configuration details for Scenario 4.2 (motorway).

UC4.2_motorway	Settings	Notes
Road section length	4.3 km	• both directions
Road priority	3	
Allowed road speed	• 36.11 m/s • 27.78 m/s (700 m in front of the safety zone before entering the work zone area) • 22.22 m/s around the work zone	• 130 km/h • 100 km/h • 80 km/h
Number of nodes	9	• n0 – n8
Number of edges	16	• both directions
Number of O-D relations	2	• from n0 to n8 • from n8 to n0
Number of lanes	4	• both directions
Construction location	from n4 to n5	• 150 m
Closed edge[3,4] (defined in the file: closeLanes.add.xml)	workzone	• the leftmost lane (150 m)
	safetyzone1	• the leftmost lane (100 m)
	safetyzone2	• the leftmost lane (100 m)
Filenames	• network: UC4_2_urban.net.xml • lane closure: closeLanes.add.xml • traffic signs: shapes.add.xml	

Intended control of lane usage

A Lane Change Assistant service is providing lane change advice to CAVs (G2) upstream of the work zone to facilitate merging in the non-blocked right lane. Some CAVs cannot merge on the non-blocked lane due to surrounding traffic and cannot pass the construction site in automated mode. Thus, they perform dynamic ToCs.

Network layout

Road segments

n0→n1: Insertion and backlog area (300 m)
n1→n3: Approaching area (1500 m)
n3→n4: Safety area (100 m)
n4→n5: Work zone (150 m)
n5→n6: Safety area (100 m)
n6→n8: Leaving area (500 m)
n8→n0: Opposite direction (2650 m)

3.2.4.2.3 CAV behaviour

Explicit flow charts depicting the behaviour of CAVs (G1) and CAVs (G2) in the context of Scenario 4.2 are shown in Figure 90. The depicted behaviour coincides with the traffic management logic described in the relevant previous subsection. Additionally, CAVs (G2) are assumed to accept shorter safe gaps for lane changing within communication range due to enhanced perception provided by collective perception and data fusion. The corresponding SUMO parameter (i.e. *lcAssertive*) is adjusted appropriately in the cooperative driving area for the traffic management simulations.

***Note:** *We assume that CAVs (G2) can explicitly collaborate for cooperative lane changing in the context of the motorway scenarios. Due to limited available space for cooperative manoeuvres in the urban scenarios,* *the latter functionality is not considered and examined. Thus, the traffic management scenarios are titled "Cooperative Driving" for motorway simulations (legends are named accordingly in the corresponding results plots).*

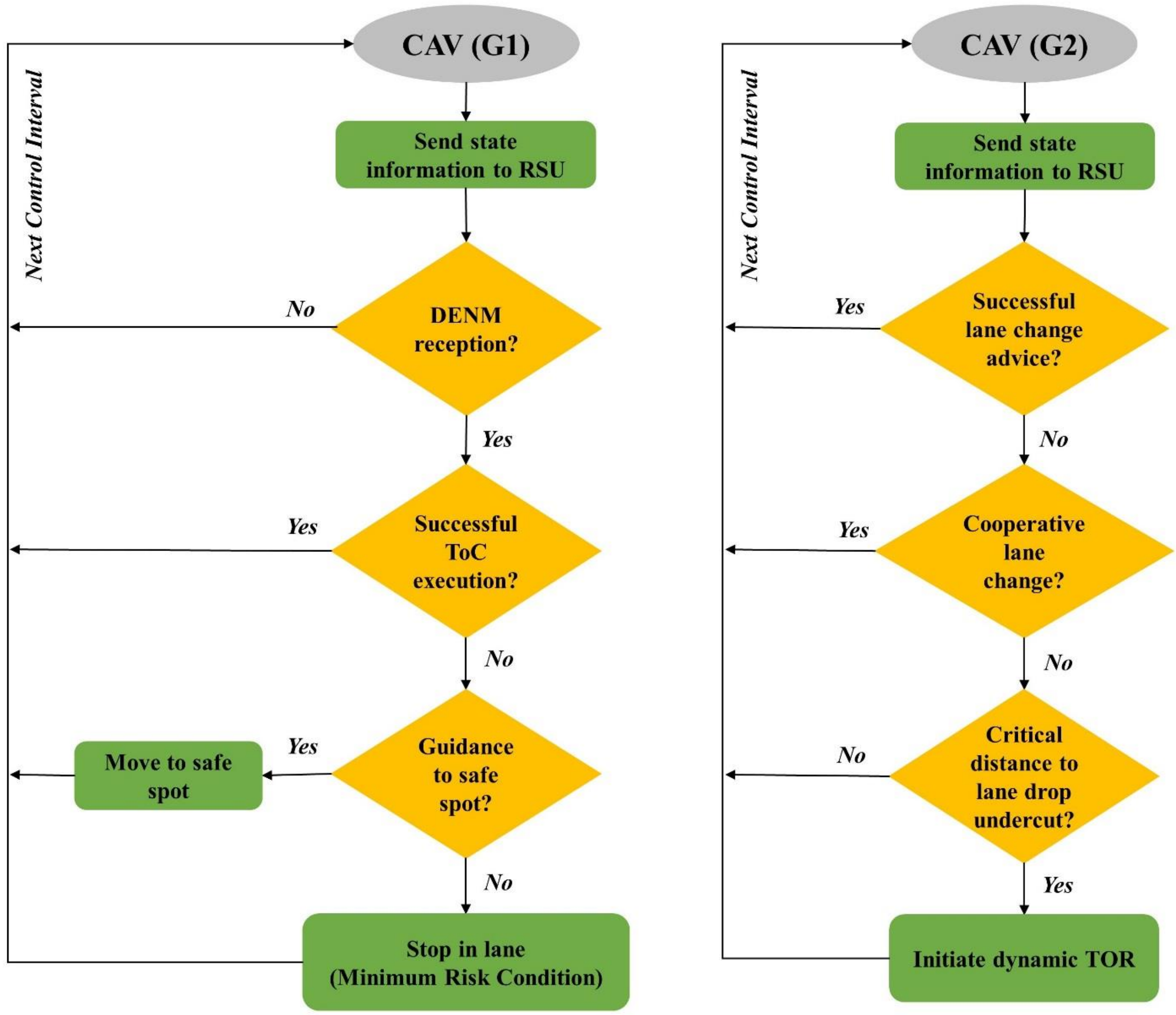


Figure 90: CAV behaviour in the context of TransAID Service 4 (2nd project iteration).

3.2.4.3 Results

Day 1 C-ITS (baseline) and Traffic Management (Service 4) scenarios are simulated for three different traffic demand levels (LOS B, C, and D) and three different vehicle mixes (Mix 1, 2, and 3) as described in Deliverable D3.1 (Mintsis et al., 2019). Furthermore, 10 simulation runs pertaining to different random seeds for each combination of demand level and vehicle mix are executed. In the following, the simulation results are analysed in the aspects of traffic efficiency, traffic dynamics, traffic safety, and environmental impacts. Simulation results are explicitly presented for urban and motorway traffic conditions.

3.2.4.3.1 Urban Network

3.2.4.3.1.1 Impacts on traffic efficiency

Network-wide impacts

The length of the urban network in Scenario 4.2 is 1.85 km (westbound direction) and the speed limit is 50 km/h. Thus, a vehicle travelling at speed limit needs 1.2 min to traverse 1 km. Figure 91 depicts the average travel time required by a vehicle to travel 1 km for each parameter combination (traffic demand level – vehicle mix) and examined scenario (Day 1 C-ITS – Traffic Management). Traffic is free flowing for LOS B and C irrespective of the CV/CAV share since travel time per kilometre travelled is marginally higher than 1.2 min. However, it can be observed that travel time is slightly lower for the Traffic Management case during uncongested conditions.

Free-flow traffic conditions are also maintained for parameter combination D/1 since travel time per kilometre travelled slightly increases to 1.3 – 1.4 min for both Day 1 C-ITS and Traffic Management simulations. A further increase (1.6 min) in travel time is observed for D/2 but traffic conditions become congested for the highest demand scenario and maximum share of CVs/CAVs in the fleet when Day 1 C-ITS scenario is considered. On the other hand, the traffic management plan achieves significantly better performance in terms of traffic efficiency for the latter parameter combination. The reason for the improved performance in the Traffic Management scenario is multifold:

a. the “MRM_CAV_01” (being stopped after MRM) is guided to the safe spot
b. CAVs (G2) accept shorter gaps for lane changing in the cooperative driving area (communication range) due to enhanced perception
c. CAVs (G2) receive lane change advice to prevent dynamical TOR triggering

Finally, it is noted that according to the network-wide traffic efficiency results, the negative impacts of the “MRM_CAV_01” (being stopped after MRM) materialise only for the highest traffic demand level and maximum share of CVs/CAVs in the fleet mix. When the arrival rate of vehicles is lower (LOS B and C), the queue formed behind the “MRM_CAV_01” dissolves faster thus not generating a traffic breakdown for the Day 1 C-ITS scenarios.

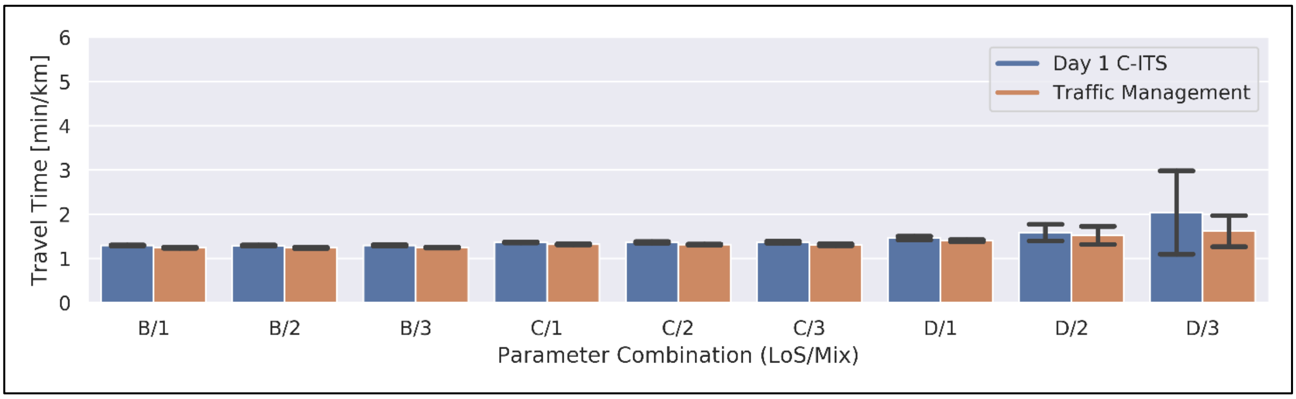


Figure 91: Average travel time (min/km) for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Traffic Management (Service 4) simulations.

Local impacts

Based on the aforementioned network-wide statistics regarding traffic efficiency we also present the corresponding local impacts for D/3 in terms of speed and flow tempo-spatial plots. The latter parameter combination was selected since Figure 91 indicated that travel time can significantly decrease when traffic management is implemented. Moreover, it encompasses the highest share of CVs/CAVs (and inherently CAVs_G2). Thus, we can verify that traffic management can alleviate the most detrimental impacts of: a) ToCs upon DENM reception, and b) dynamical TOR triggering upstream of the work zone.

Figure 92 indicates that the "MRM_CAV_01", which is injected in the beginning of the simulation in the network, stops after MRM in the open lane during the Day 1 C-ITS scenario, thus generating a traffic breakdown that affects the road section upstream of the work zone for the whole simulation timeline (left bottom plot). On the contrary, the "MRM_CAV_01" is guided to the safe spot on the blocked lane during the Traffic Management scenario, hence preventing the propagation of traffic disruption upstream towards the network entry (right bottom plot). Moreover, it can be observed that the traffic management measures ensure an improved level of service (increased speeds) by preventing inefficient traffic operations in the proximity of the work zone (smoother merging in the non-blocked lanes). Thus, more vehicles can be serviced during the simulated hour (right top plot).

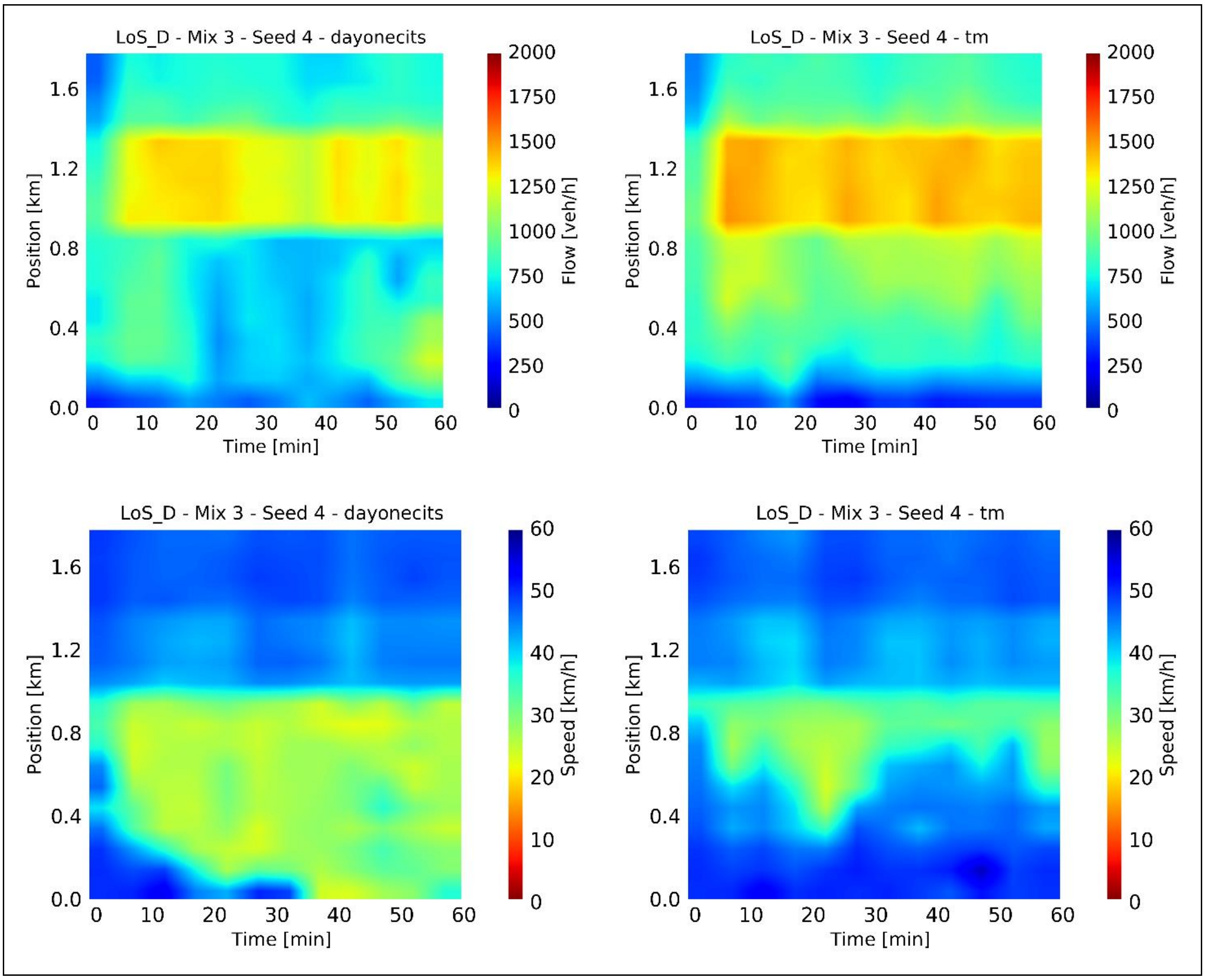


Figure 92: Exemplary speed and flow tempo-spatial diagrams for use case 4.2 (LOS D, Mix 3, Seed 4, urban network). The left column corresponds to Day 1 C-ITS (baseline) scenario and the right column to the Traffic Management (Service 4) scenario.

3.2.4.3.1.2 Impacts on traffic dynamics

Average throughput is used as KPI to elaborate on traffic dynamics hereafter. Figure 93 shows the number of vehicles that were serviced (exited the network) within an hour of simulation per parameter combination and examined scenario (Day 1 C-ITS – Traffic Management). Considering that traffic demand input was 825 veh/h for LOS B, 1155 veh/h for LOS C, and 1386 veh/h for LOS D, it is clear that input traffic can be serviced (on average) almost for every parameter combination. However, we can also observe a marginal decrease of throughput for increased CV/CAV share and traffic demand levels LOS C and D. The latter decrease can be ascribed to ToC/MRM operations (i.e. ToC preparation phase, dynamical TOR triggering near the work zone, MRM events) which generate traffic flow disturbances upstream of the work zone. Nonetheless, the decrease is less prominent for Traffic Management scenario and parameter combination D/3, when CAV (G2) lane changing becomes less conservative within communication range and lane change advice provision from the RSI side reduces dynamical TOR triggering (and subsequent MRMs).

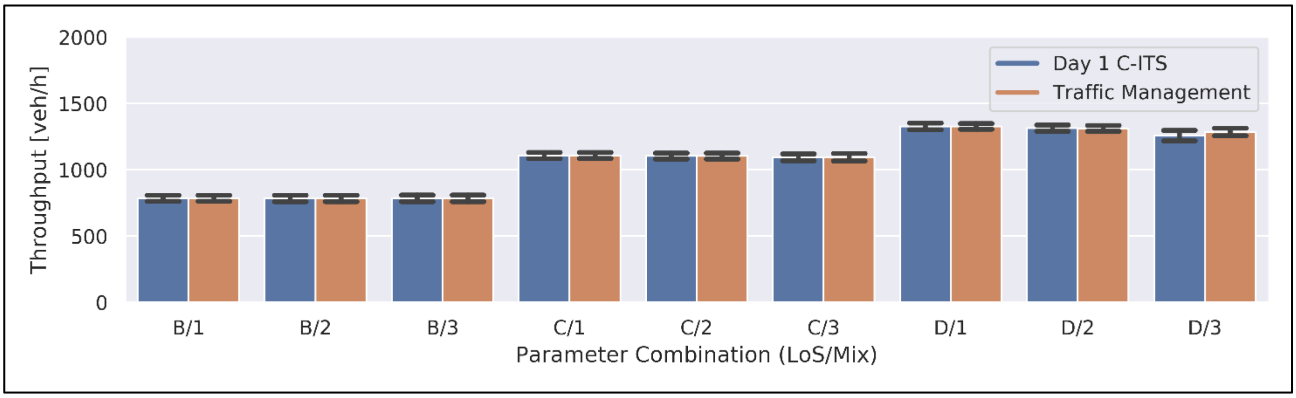


Figure 93: Throughput (veh/h) for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Traffic Management (Service 4) simulations.

Lane changing is also investigated as a factor significantly affecting traffic dynamics. The number of lane changes per driven kilometre is used as KPI in this case. According to Figure 94, approximately one lane change is performed per 2 kilometres. The reported numbers are reasonable, considering that the urban network stretches to 1.8 km and that one lane change is required for a vehicle inserted on the blocked lane to reach its destination (by passing the work zone).

Moreover, Figure 94 indicates that lane changing is less intensive for every parameter combination when Traffic Management scenarios are considered. This finding is justifiable since CAVs (G2) receive lane change or lane keep advice 600 m upstream of the work zone and thus their lane change activity is controlled for a significant portion of the urban network (tactical manoeuvring diminishes for CAVs (G2) along the latter road portion). Additionally, lane change behaviour is homogenised within the RSU’s communication range, which renders traffic operations smoother and tactical manoeuvring less frequent.

Lane changes are slightly reduced for higher shares of CVs/CAVs in the case of Day 1 C-ITS scenarios. The latter result is expected since conservative CAV lane changing creates more turbulence around the lane drop area and thus there is less space for tactical lane changing. Likewise, higher traffic demand (LOS D) yields denser traffic conditions in the proximity of the work zone which results in less space for tactical lane changing and thus reduced lane change intensity.

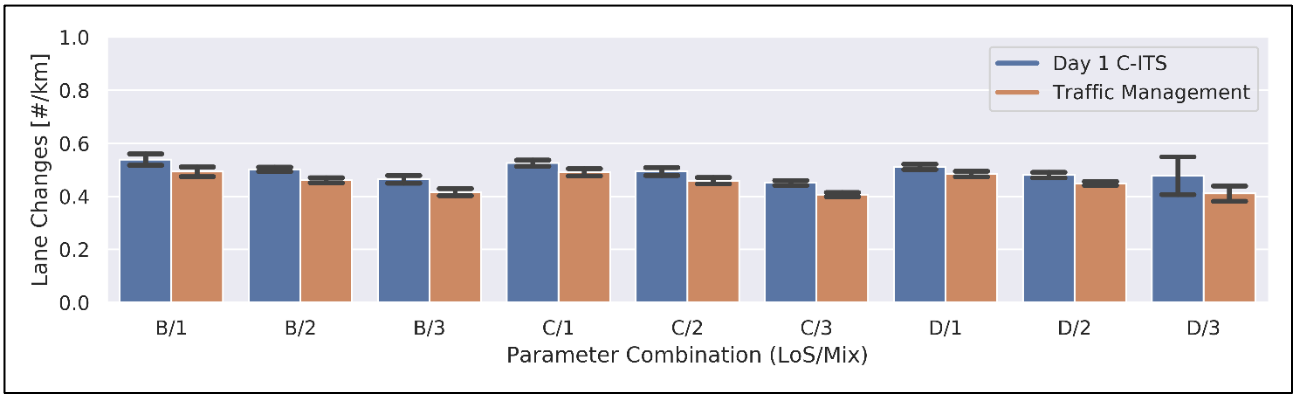


Figure 94: Lane changes per driven kilometre for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Traffic Management (Service 4) simulations.

Transitions of control are expected to exert significant influence on traffic dynamics. In the context of this analysis, system-initiated take-over requests (TORs) are considered as KPI for the assessment of traffic dynamics. Figure 95 depicts the total number of issued TORs during simulation timeline per parameter combination and tested scenario.

The number of TORs for CVs and CAVs (G1) is fixed per simulation since these vehicles execute ToC when DENM messages are received. Thus, differences between Day 1 C-ITS and Traffic Management scenarios can explicitly result from dynamic TOR triggering behaviour of CAVs (G2). During uncongested conditions when there is available space for CAVs (G2) to change lane unimpeded from surrounding traffic upstream of the work zone the number of TORs is similar between the tested scenarios. On the contrary, it can be observed that lane advice provision in the case of Traffic Management scenario can reduce dynamic TORs during congested conditions (D/3). Considering that the latter TORs occur in the close proximity of the work zone and can also lead to MRMs explains the increased traffic disruption prevailing in Day 1 C-ITS scenario (Figure 4.5 and 4.6).

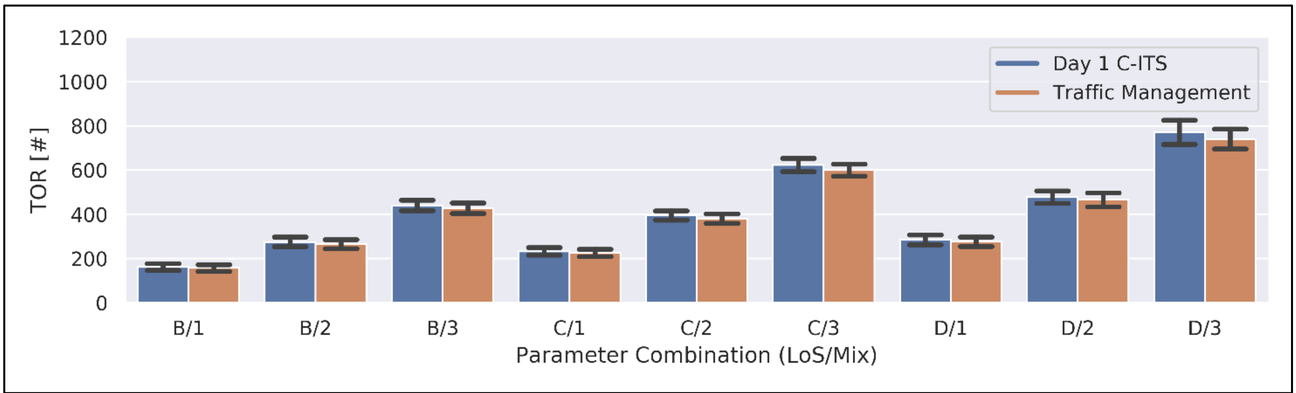


Figure 95: Number of take-over requests (TORs) for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Traffic Management (Service 4) simulations.

3.2.4.3.1.3 Impacts on traffic safety

In the second iteration we analyse traffic safety both network-wide and locally. On the network-wide scale we use the same KPI as in the first project iteration (i.e. the number of critical TTC events less than 3 sec). Locally we evaluate aggregated TTC distributions upstream of the work zone.

Network-wide impacts

Figure 4.10 illustrates the average number and standard deviation of safety critical events for every examined parameter combination and tested scenario. We can observe that the average number of safety critical events increases with increased share of CVs/CAVs when controlling for traffic demand level. The latter finding coincides with observations made based on simulation results of the first project iteration. Conservativeness of CV/CAV lane change behaviour (especially in Day 1 C-ITS scenario) and ToC/MRM operations induce higher numbers of safety critical events.

Figure 96 also indicates that increasing traffic demand leads to increased occurrence of safety critical events. As explained in the analysis of the traffic efficiency results, traffic is free flowing for parameter combinations B/1 – D/2. However, as demand increases (from LOS B to LOS D), traffic becomes denser and the vehicle interactions in the mixed traffic stream are rendered more complex.

Thus, denser traffic generates higher collision risk when traffic flow remains in the uncongested regime and there is space available for vehicle interactions.

Notably, traffic management mitigates collision risk compared to Day 1 C-ITS scenario for every examined parameter combination. Reduced frequency of dynamic TORs from CAVs (G2) (due to lane change/keep advice provision) and homogenised lane change behaviour upstream of the work zone result in more safe vehicle interactions along Transition Areas.

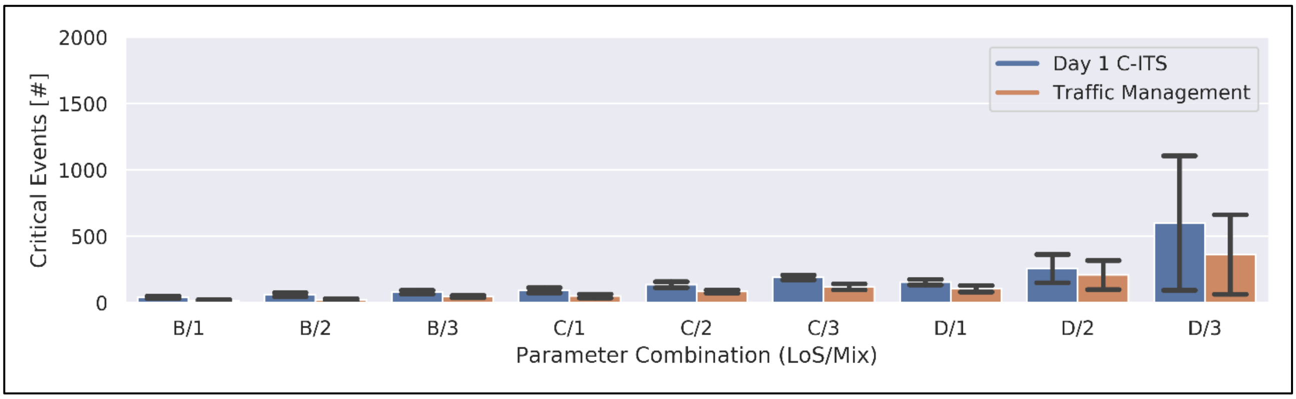


Figure 96: Average number of safety-critical events (TTC < 3.0 s) for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Traffic Management (Service 4) simulation.

Local impacts

When looking at the spatial distribution of safety critical events, local impacts can be further identified. The TTC density plots feature the aggregated number of critical TTCs of 10 seeds (per LOS/Mix) marked as bins along the urban network. Each plotted bin means that at least one TTC occurred at this position. The colour of a bin then indicates the amount of TTCs at this marked position. For example, when several TTCs concentrate within a certain area, the colours translate as a spatial density for interpretation of the TTC distribution.

The focus of the analysis on the local scale is placed explicitly on parameter combination D/3 where most of the safety critical events were observed in the bar plots of the network-wide analysis. Figure 97 (upper plot) indicates that there are two main areas where safety critical events are generated for the Day 1 C-ITS scenario: a) in front of the work zone (location = 1.0 km), and b) downstream of the DENM reception point (location = 0.4 – 0.55 km). Safety critical events on the right lane upstream of the work zone (lane centre at y = 55.3) occur due to braking episodes which take place to facilitate merging of stopped vehicles (located on the left lane in front of the work zone) into the open lane. On the other hand, safety critical events on the left lane (lane center at y = 58.3) occur due to hard braking events from vehicles which cannot freely merge onto the right open lane. Safety critical events taking place downstream of the DENM reception point (location = 0.4 – 0.55 km) are induced due to “MRM_CAV_01” stopping in lane for a few seconds in this area.

On the other hand, Figure 97 (lower plot) indicates that traffic management measures prevent the occurrence of safety critical events downstream of the DENM reception point (location = 0.4 – 0.55 km) since “MRM_CAV_01” is guided to the safe spot instead of stopping in lane. Moreover, we can observe that several safety critical events previously occurring due to lane change activity in the Day 1 C-ITS scenario are now resolved due to provision of lane change/keep advice to CAVs(G2) and homogenised lane change behaviour within the traffic management area. Overall, the density plots also verify that collision risk reduces when infrastructure-assisted management measures are applied upstream of the work zone.

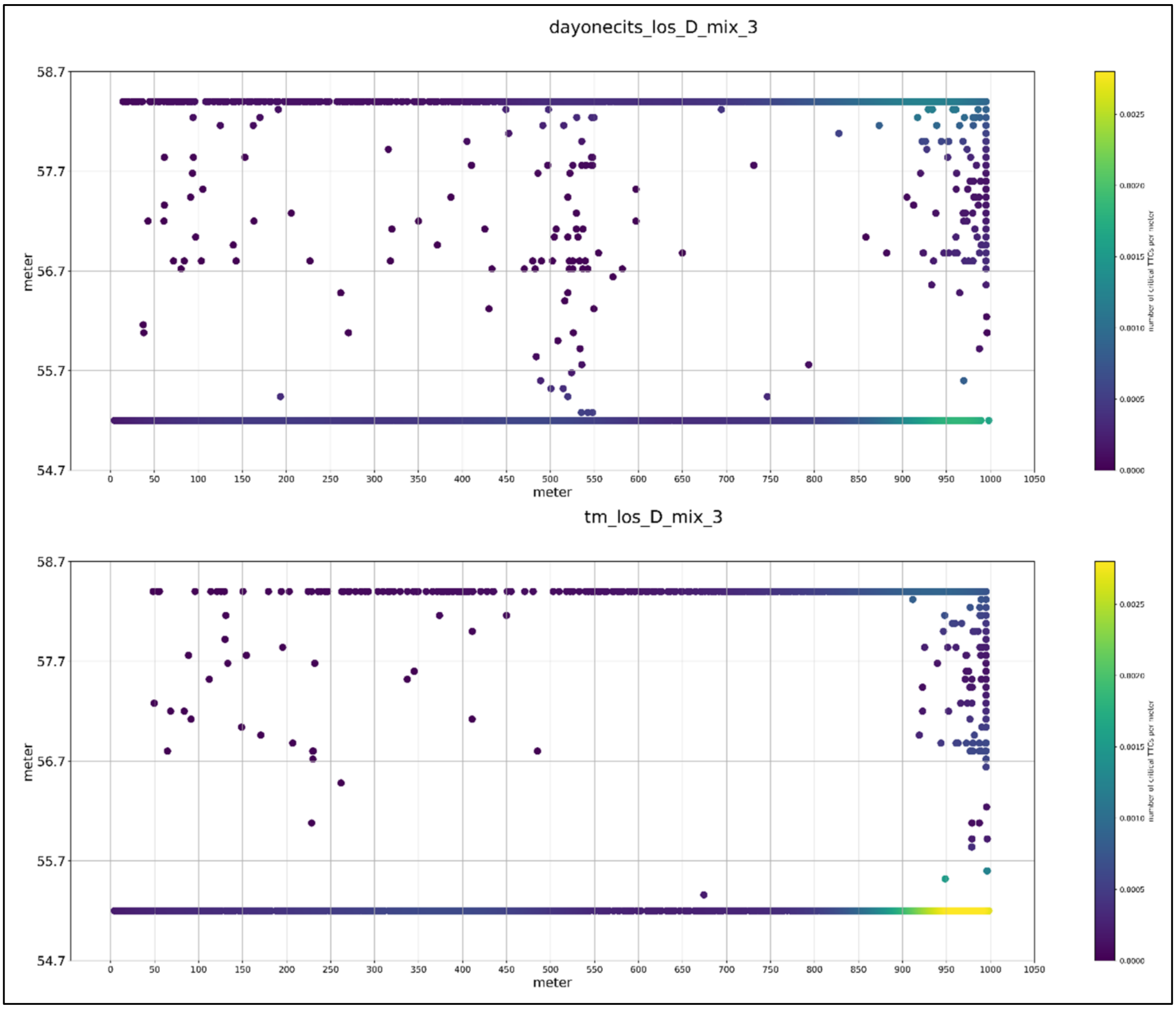


Figure 97: Spatial distribution of critical TTCs (< 3 sec) for use case 4.2 (urban) and parameter combination D/3. Upper plot depicts Day 1 C-ITS scenario results; lower plot depicts Traffic Management scenario results. Colours indicate the number of critical TTCs.

3.2.4.3.1.4 Environmental impacts

The environmental impacts of system-initiated control transitions in the context of Scenario 4.2 are assessed in terms of CO_2 emissions per travelled kilometre. Figure 98 depicts the average CO_2 emissions per travelled kilometre for the examined parameter combinations and tested scenarios. We notice that the CO_2 emissions are slightly lower for Traffic Management scenarios during uncongested conditions. This finding complies with traffic efficiency results which indicate that travel times and speed patterns are marginally improved for Traffic Management scenarios and free flow traffic conditions. On the other hand, CO_2 emissions are not significantly different between Day 1 C-ITS and Traffic Management scenarios when traffic disruption occurs as a result of higher demand levels (LOS D).

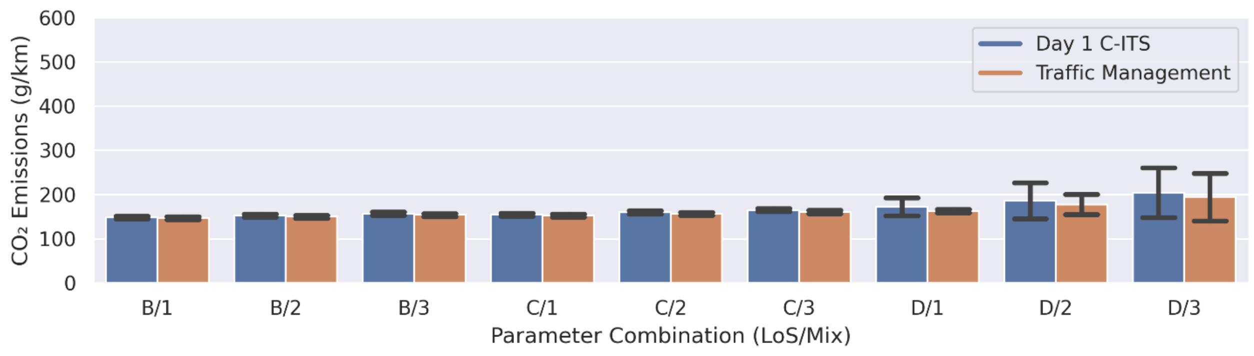


Figure 98: Average CO_2 emissions per driven kilometre for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Traffic Management (Service 4) simulations.

3.2.4.3.2 Motorway Network

3.2.4.3.2.1 Impacts on traffic efficiency

Network-wide impacts

The length of the motorway network in Scenario 4.2 is 2.65 km (westbound direction) and the average speed limit is 115 km/h (the speed limit gradually drops from the insertion edge towards the work zone for safety reasons). Thus, a vehicle travelling with speed limit needs approximately 0.52 min to traverse 1 km. Figure 99 depicts the average travel time required by a vehicle to travel 1 km for each parameter combination and tested scenario.

We can observe that traffic is free flowing for both Day 1 C-ITS and Cooperative Driving scenarios in LOS B. However, travel time is marginally lower for Cooperative Driving. On the other hand, congested conditions prevail for LOS C and D when travel time escalates with increasing demand and share of CV/CAVs (higher ToC/MRM frequency). Congestion in LOS C and D also results from complex vehicle interactions due to higher driving speeds on the motorway network. Particularly, ToC/MRM operations can induce sharper braking events for following vehicles with higher travelling speeds. Moreover, higher speeds mean longer safe gaps for lane changing. Nonetheless, cooperative driving results in significantly improved travel times compared to Day 1 C-ITS due to the following reasons:

a. the “MRM_CAV_01” (being stopped after MRM) is guided to the safe spot
b. CAVs (G2) accept shorter gaps for lane changing in the cooperative driving area (communication range) due to enhanced perception
c. CAVs (G2) receive lane change advice to prevent dynamical TOR triggering
d. infrastructure assistance is provided earlier to CVs/CAVs due to increased communication range
e. cooperative lane changing is feasible among CAVs (G2) to prevent dynamical TOR triggering

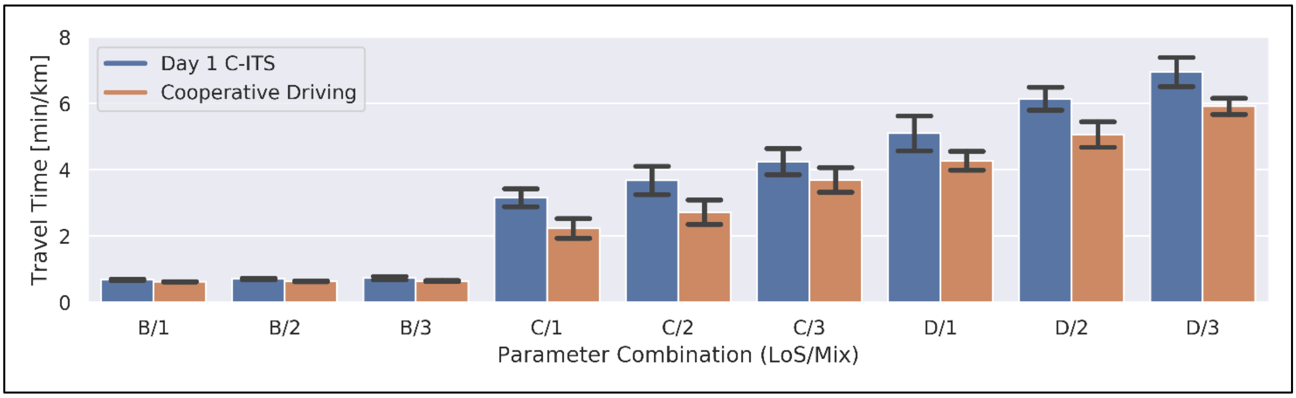


Figure 99: Average travel time (min/km) for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Cooperative Driving (Service 4) simulations.

Local impacts

Based on the aforementioned network-wide statistics regarding traffic efficiency we also present the corresponding local impacts for parameter combination C/1 in terms of speed and flow tempo-spatial plots. The latter parameter combination is representative for demonstrating the improved performance of Cooperative Driving scenario in congested conditions. Moreover, it encompasses the lowest share of CVs/CAVs (and inherently CAVs (G2)). Thus, we can verify that cooperative driving can yield significant benefits in mixed traffic scenarios when a small proportion of the vehicle population is controlled.

Figure 100 indicates that “MRM_CAV_01” which is injected in the beginning of the simulation in the network, expedites the propagation of congestion towards the network entry (upstream of location = 1.0 km and beyond time = 3 min) if it is not guided to the safe spot (left bottom plot). For Day 1 C-ITS scenario congestion reaches network entry and stop-and-go traffic prevails upstream of the work zone. On the contrary, the “MRM_CAV_01” is guided to the safe spot on the blocked lane during the Cooperative Driving scenario, hence preventing the propagation of traffic disruption upstream towards the network entry (right bottom plot). Moreover, it can be observed that the traffic management measures applied in the Cooperative Driving scenario, ensure an improved level of service (increased speeds) by preventing inefficient traffic operations in the proximity of the work zone (smoother merging on the non-blocked lanes). Therefore, more vehicles can be serviced during the simulated hour (right top plot).

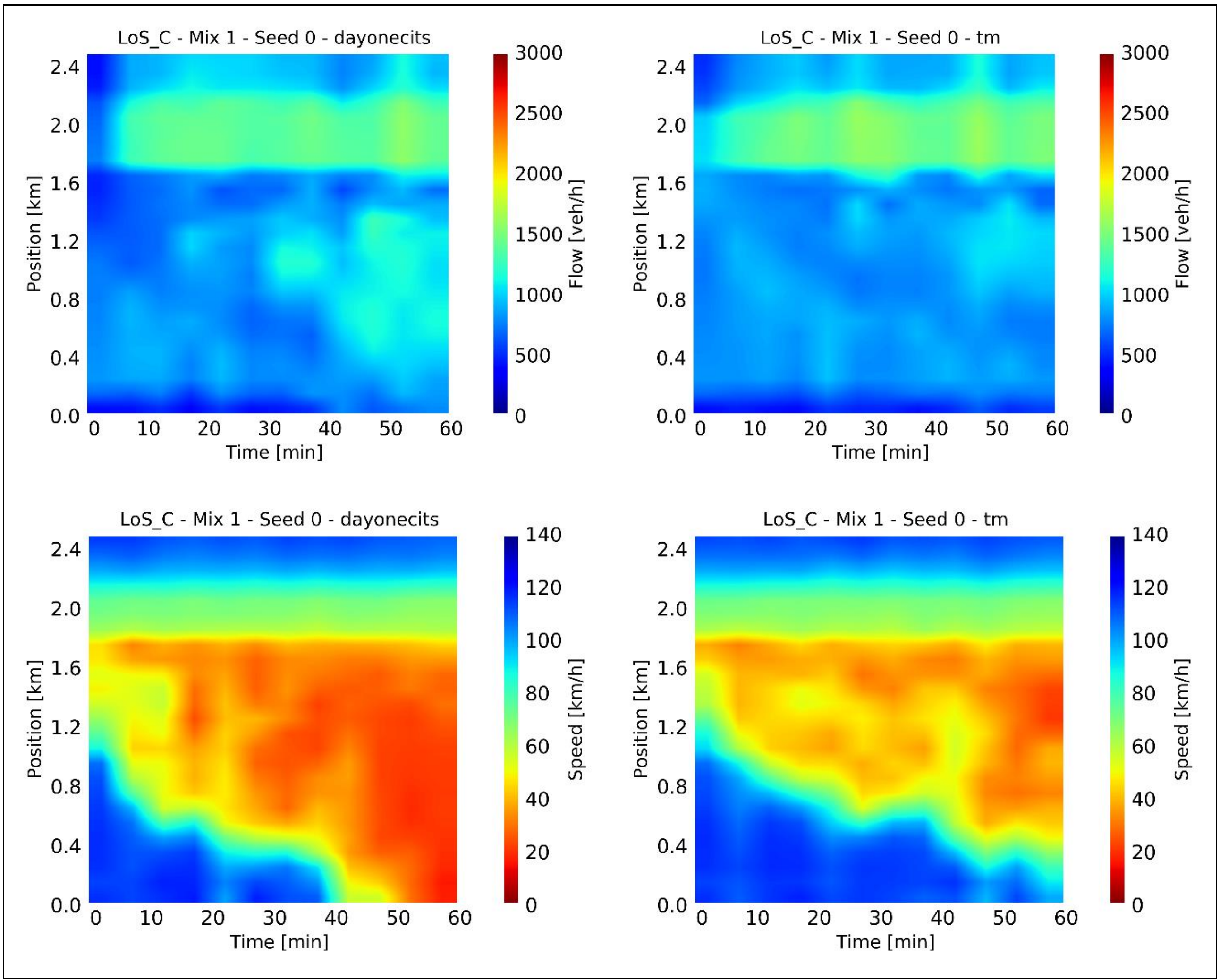


Figure 100: Exemplary speed and flow tempo-spatial diagrams for use case 4.2 (LOS C, Mix 1, Seed 0, motorway network). The left column corresponds to Day 1 C-ITS (baseline) scenario and the right column to the Cooperative Driving (Service 4) scenario.

3.2.4.3.2.2 Impacts on traffic dynamics

Average throughput is used as KPI to elaborate on traffic dynamics hereafter. Figure 101 shows the number of vehicles that were serviced (exited the network) within an hour of simulation per parameter combination and tested scenario. Considering that traffic demand input was 1155 veh/h for LOS B, 1617 veh/h for LOS C, and 1940 veh/h for LOS D, it is clear that input traffic can only be serviced on average for traffic demand level LOS B.

However, we can also observe a decrease of throughput for increased CV/CAV share and traffic demand levels LOS C and LOS D. The latter decrease can be ascribed to conservativeness of CAV lane changing and ToC/MRM operations (i.e. ToC preparation phase, dynamical TOR triggering near the work zone, MRM events) which are more frequent for increased CV/CAV share. Interestingly, average throughput is similar between LOS C and D for the same vehicle mixes. Thus, it can be concluded that the network has already reached capacity in LOS C.

Nonetheless, we can observe that capacity increases in Cooperative Driving scenario compared to Day 1 C-ITS one. As aforementioned, infrastructure assistance, enhanced perception, and cooperative lane changing result in more efficient traffic operations which positively affect network throughput as well.

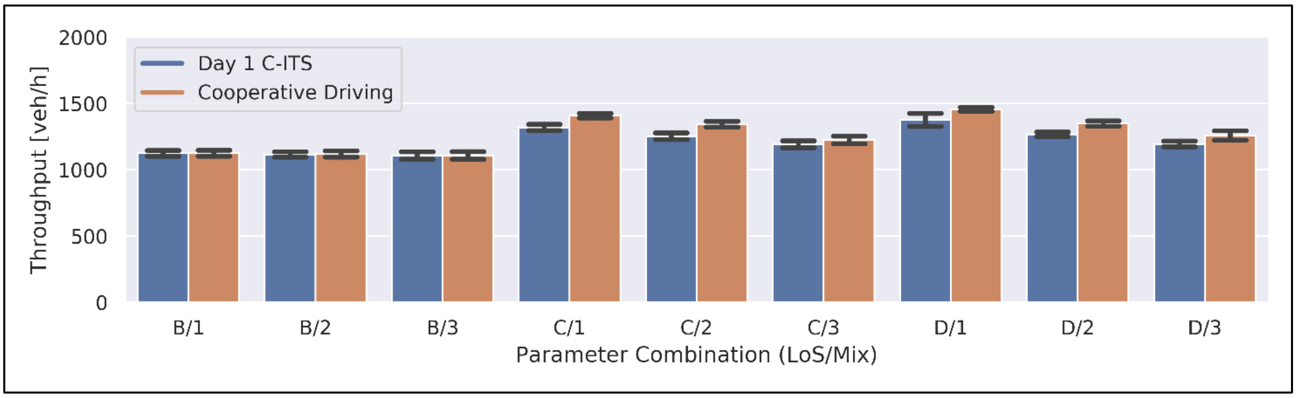


Figure 101: Throughput (veh/h) for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Cooperative Driving (Service 4) simulations.

Lane changing is also investigated as a factor significantly affecting traffic dynamics. The number of lane changes per travelled kilometre is used as KPI in this case. According to Figure 102, approximately one lane change is performed per 2.5 kilometres. Considering that the motorway network stretches to 2.65 km and that one lane change is required for a vehicle inserted on the blocked lane to reach its destination (by passing the work zone) the reported numbers are reasonable.

Moreover, Figure 102 indicates that lane changing is less intensive for uncongested conditions when cooperative driving scenarios are considered. This finding is justifiable since CAVs(G2) receive lane change or lane keep advice 1200 m upstream of the work zone and thus their lane change activity is controlled for a significant portion of the urban network (tactical manoeuvring diminishes for CAVs (G2) along the latter road portion). Additionally, lane change behaviour is homogenised within the cooperative driving area which renders traffic operations smoother and tactical manoeuvring less frequent.

On the other hand, lane change intensity is similar between Day 1 C-ITS and Cooperative Driving scenarios for congested conditions and low to moderate shares of CVs/CAVs. This is explicable considering the limited available space for lane changing during congestion and the lesser opportunities for controlling CAV lane change behaviour due to lower CAV share. However, higher CAVs shares (Mix 3) provide more opportunities for guiding and keeping CAVs on preferred lanes (lane change/keep advice – cooperative lane changing) especially when the network is not totally occupied by jammed traffic (LOS C). In this latter case, lane change intensity can decrease, thus inducing less traffic turbulence.

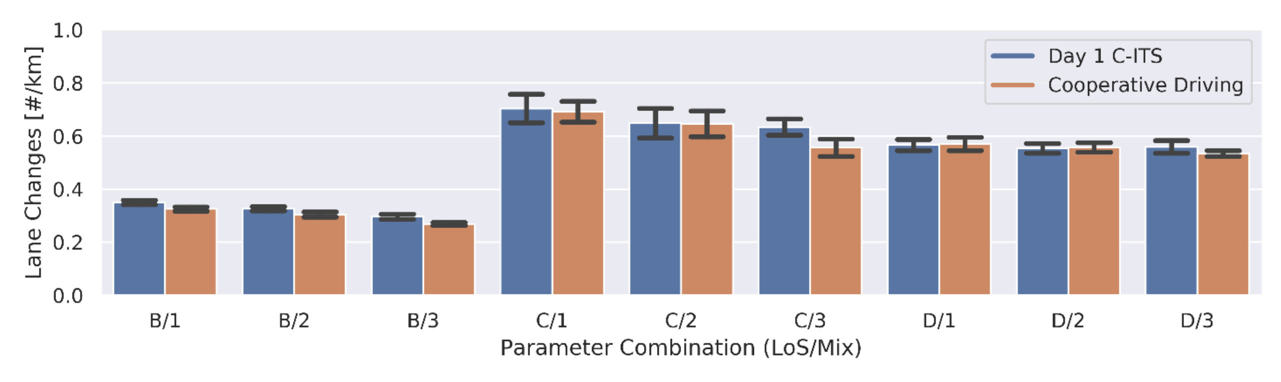


Figure 102: Lane changes per driven kilometre for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Cooperative Driving (Service 4) simulations.

Figure 103 depicts the total number of issued TORs during simulation timeline per parameter combination and tested scenario. The number of TORs for CVs and CAVs (G1) is fixed per simulation since these vehicles execute ToC when DENM messages are received. Thus, differences between Day 1 C-ITS and Cooperative Driving scenarios can explicitly result from dynamic TOR triggering behaviour of CAVs (G2).

During uncongested conditions when there is available space for CAVs (G2) to change lane unimpeded upstream of the work zone the number of TORs is similar between the tested scenarios. On the contrary, it can be observed that lane change/keep advice provision, cooperative lane changing and homogenised lane change behaviour (within communication range) in the case of Cooperative Driving scenario can reduce dynamic TORs during congested conditions (LOS C and D). Considering that the latter TORs occur in the close proximity of the work zone and can also lead to MRMs explains the increased traffic disruption prevailing in Day 1 C-ITS scenario (Figure 99 and Figure 100).

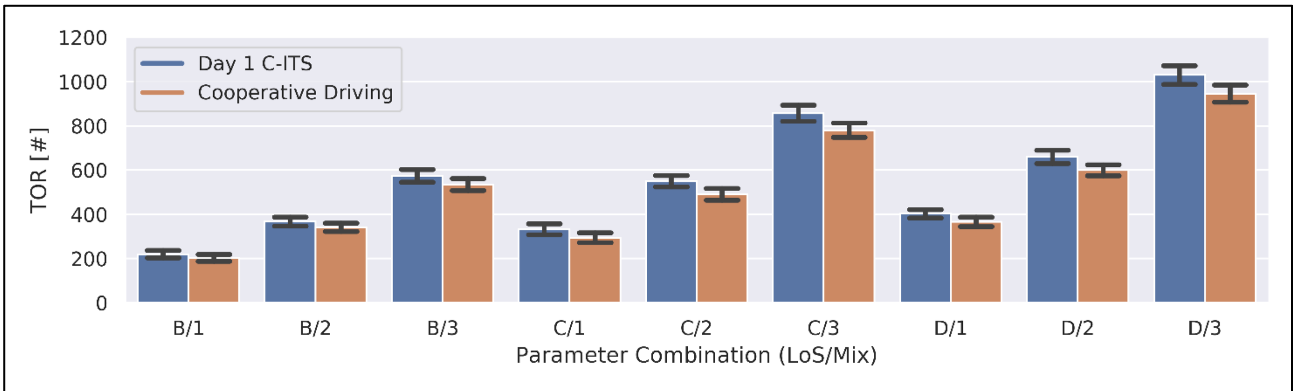


Figure 103: Number of take-over requests (TORs) for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Cooperative Driving (Service 4) simulations.

3.2.4.3.2.3 Impacts on traffic safety

Network-wide impacts

Figure 104 illustrates the average number and standard deviation of safety critical events for every examined parameter combination and tested scenario. We can observe that the average number of safety critical events increases with increased share of CVs and CAVs when controlling for traffic demand level. The latter finding coincides with observations made based on simulation results of the first project iteration. Conservativeness of CV/CAV lane change behaviour (especially in Day 1 C-ITS scenario) and ToC/MRM operations induce higher numbers of safety critical events.

Figure 104 also indicates that increasing traffic demand leads to increased occurrence of safety critical events. Denser traffic generates higher collision risk when traffic flow remains in the uncongested regime and there is space available for vehicle interactions (LOS B). However, it is also shown that safety critical events increase excessively (more than one critical event per simulated vehicle) during congested conditions (LOS C and D). The latter result is rather contradictory considering that there is limited space for high-speed and complex vehicle interactions during congestion. Thus, unless the spatial and temporal distribution of safety critical events is analysed it is difficult to conclude on the assessment of traffic safety.

Notably, cooperative driving mitigates collision risk compared to Day 1 C-ITS scenario for uncongested conditions (as in the urban network as well). Reduced frequency of dynamic TORs from CAVs (G2) (due to lane change/keep advice provision) and homogenised lane change behaviour upstream of the work zone result in more safe vehicle interactions. However, safety benefits diminish with increasing demand that generates congestion as aforementioned.

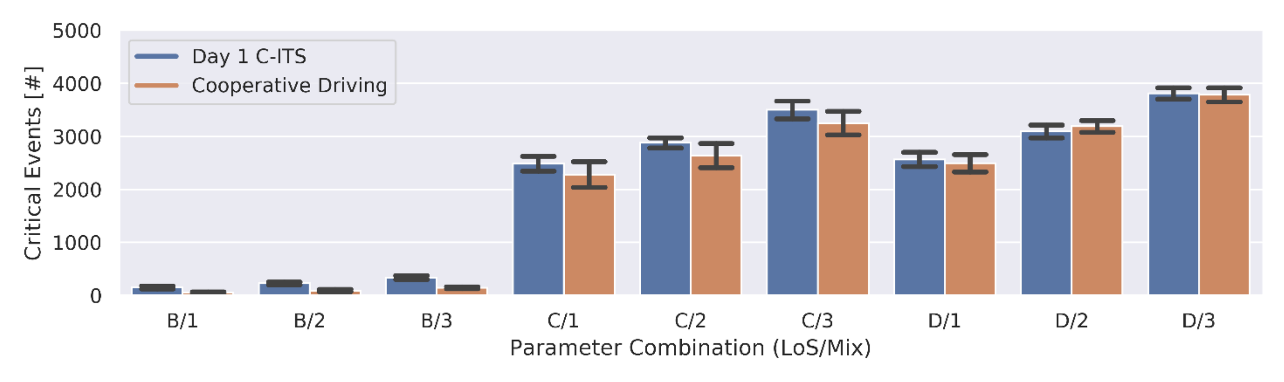


Figure 104: Average number of safety-critical events (TTC < 3.0 s) for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Cooperative Driving (Service 4) simulations.

Local impacts

The focus of the analysis on the local scale is placed on congested conditions and specifically parameter combination C/1. According to the network-wide results Cooperative Driving scenario yields lesser safety critical event compared to Day 1 C-ITS. Figure 105 (upper plot) indicates that safety critical events occur for both car-following and lane changing reasons in Day 1 C-ITS scenario. However, TTC density is significantly higher on the left blocked lane where several vehicles need to brake since they cannot merge unimpeded in the non-blocked lane (right lane changes prevail for strategic reasons). The scatter of TTC events is similar for the cooperative driving scenario as shown in Figure 105 (lower plot), but due to lesser congestion on the network entrance collision risk drops.

However, it is also shown in the spatial density TTC plots that safety critical events increase excessively during congested conditions. As aforementioned, the latter result warrants further investigation, since there is limited space for high-speed and complex vehicle interactions during congestion.

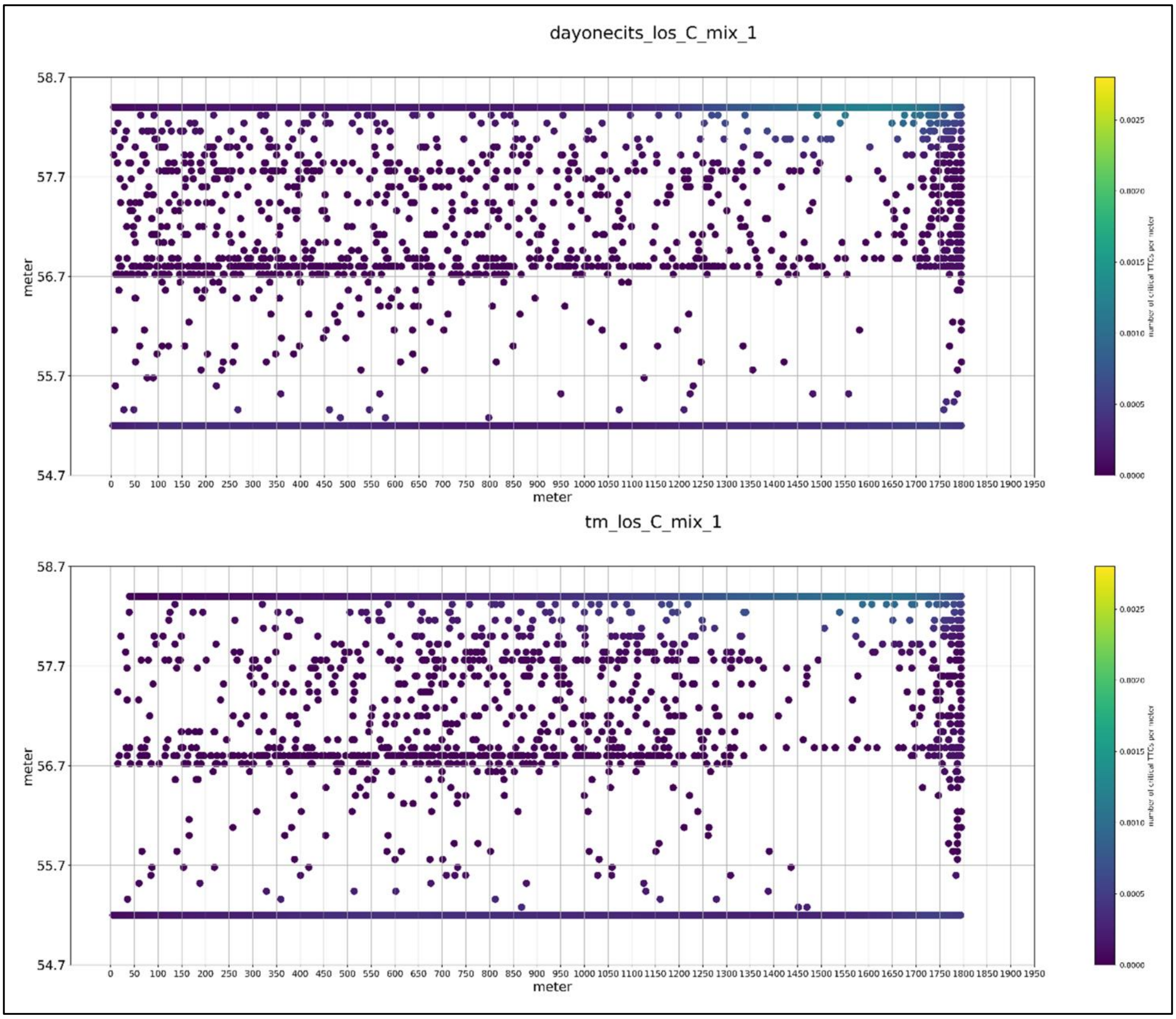


Figure 105: Spatial distribution of critical TTCs (< 3sec) for use case 4.2 (motorway) and parameter combination C/1. Upper plot depicts Day 1 C-ITS scenario results; lower plot depicts Cooperative Driving scenario results. Colours indicate the number of critical TTCs shown with discrete plotted bins.

3.2.4.3.2.4 Environmental impacts

The environmental impacts of system-initiated control transitions in the context of Scenario 4.2 are assessed in terms of CO_2 emissions per kilometre travelled. Figure 106 depicts the average CO_2 emissions per travelled kilometre for the examined parameter combinations and tested scenarios. In general, the trends observed for emissions match those for travel times. CO_2 emissions gradually increase from 240 g/km (B/1) to 750 g/km (D/2) for Day 1 C-ITS scenarios as a result of the increase in traffic disruption (longer travel times). Maximum CO_2 emission rate is observed for parameter combination D/3, when ToC operations and the behaviour of the "MRM_CAV_01" intensify traffic congestion. The excessive CO_2 emissions rates for LOS C and D are observed due to stop-and-go traffic, which extends from the work zone until the motorway network entry.

Figure 106 also indicates that Cooperative Driving achieves improved performance in terms of environmental benefits (especially for congested conditions) compared to Day 1 C-ITS scenarios. This result complies with reported average travel times and tempo-spatial speeds on the motorway network (Figure 99 and Figure 100), which indicate that the measures applied in the Cooperative Driving scenario yield significant CO_2 emissions reduction.

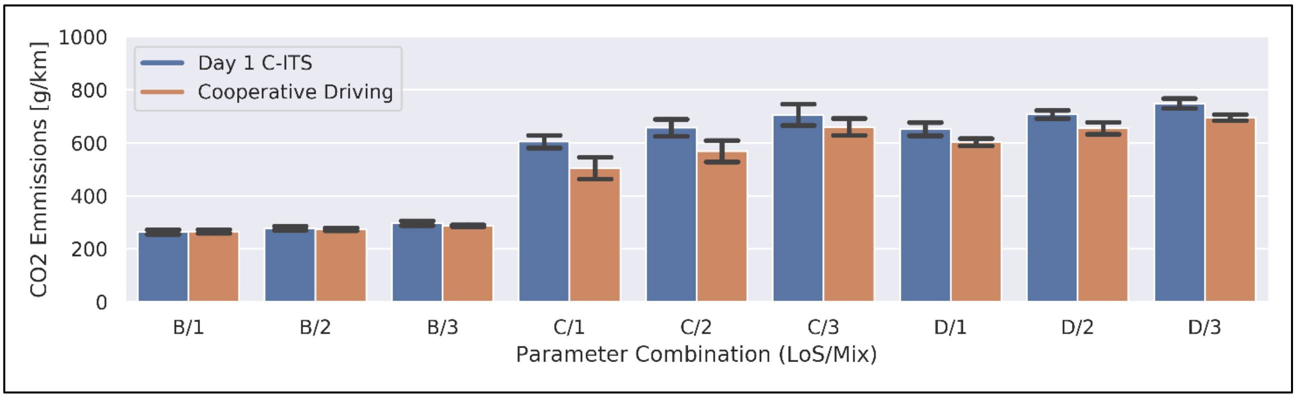


Figure 106: Average CO_2 emissions per driven kilometre for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to Day 1 C-ITS (baseline) and Cooperative Driving (Service 4) simulations.

3.2.4.4 Discussion

Simulation results for both the urban and motorway networks indicate that infrastructure-assisted traffic management and cooperative driving can generate traffic efficiency, traffic safety, and environmental benefits in the vicinity of Transitions Areas. CAV guidance to safe spots, lane advice (change/keep) provision from the RSI, and distributed cooperative manoeuvring reduce traffic disruption induced by MRMs in lane, dynamic TORs and non-homogeneous lane change behaviour in the proximity of lane drop bottlenecks (e.g., work zones). Specifically, reported results show that average travel time, shockwaves, lane change intensity, TORs, safety critical events, and CO_2 emissions reduce for Traffic Management scenarios, while throughput increases.

Moreover, it is of note that “MRM_CAV_01” stays stopped in lane after MRM only for 60 sec in Day 1 C-ITS scenarios. In cases that stop time of “MRM_CAV_01” would increase or more CAVs would stop after MRM in lane, the benefits of infrastructure-assisted traffic management would further increase. Finally, it is also expected that increased share of CAVs (G2) in the vehicle mix would result in higher rates of cooperative manoeuvring that could possibly mitigate traffic disruption and increase network capacity.

3.2.5 Scenario 4 (Use case 4.1) + Scenario 5 (Use case 5.1): Distributed safe spots along an urban corridor

3.2.5.1 Introduction

The baseline case, conducted in D3.1/2nd iteration, deals with the situation where CAVs approach a No-AD zone together with other road participants (LVs, heavy and light trucks) and some CAVs perform a MRM action. Moreover, road-side parking activities exist in the approach area. The corresponding schematic presentation is illustrated in Figure 107. The main considered parameters and actions include:

- No-AD zone begins at the position x_{NOAD}
- Parking lots 1,…,P are at position p_i with uniform capacity
- Vehicles enter the network at rate *F* [veh/h]
- MRM action takes place every interval *T*
- CAVs issue TOR at latest at the position $x_{NOAD} - d_{MRM} - d_{lead}$, where

  $$d_{MRM} = {0.5 * v(t_{TOR})^2}/{b_{MRM}}$$

  and

  $$d_{lead} = v(t_{TOR}) * T_{lead}$$

  where x_{NOAD}: the position of the beginning of the No-AD zone; d_{MRM}: the distance for executing a MRM action; d_{lead}: the duration before issuing a take-over request; t_{TOR}: time when sending a take-over request; b_{MRM}: the maximal deceleration rate during a MRM action.

- The recovering phase from a MRM action requires time *R*

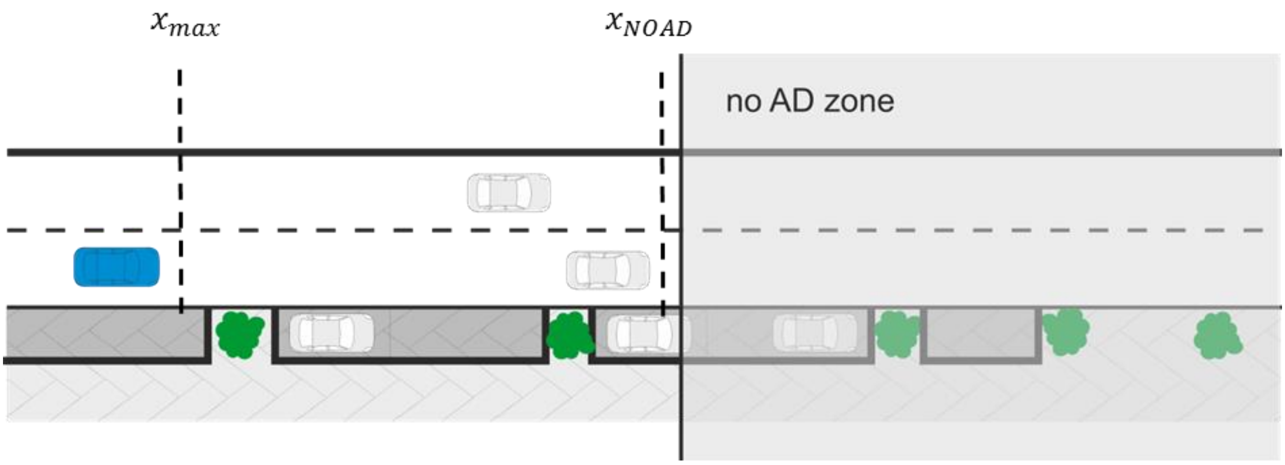


Figure 107: Schematic presentation of the scenario 4.1-5. The cross-section x_{max} illustrates the latest point, where a TOR has to be issued by Service 5 to ensure that the automated (blue) vehicle does not enter the No-AD zone. In combination with Service 4 this point corresponds to the last reachable safe spot in the scenario.

In order to minimise the impact of MRM action on traffic flow it is considered to use available parking places as safe spots so that CAVs performing a MRM can stop on the safe spots assigned by the TMC until drivers take over the control and further continue their trips in manual mode till passing the No-AD zone. The respective management mechanism includes two parts:

a) Service 5: the heuristic for distributing TORs within the controlled approaching area as implemented in the 1st iteration → x_1 [3]
b) Service 4: the newly proposed heuristic for assessing and targeting available safe spots (empty parking spaces) → safe spot i is within reach

For each CAV, at each traffic management step, we obtain the position x_1 and a tentatively reserved safe spot i. The TMC issues a TOR advice if the vehicle's current position is larger than x_1 and the reserved safe spot i is within reach.

3.2.5.2 Traffic management setup

In the following, the proposed traffic management will be described in detail and divided into two parts, i.e. traffic management logic and CAV behaviour.

3.2.5.2.1 Traffic management logic

As already mentioned the proposed traffic management logic can be divided into two components, which are Service 5 described in the first iteration and Service 4. We focus here on Service 4 and its logic. In general, Service 4 is to reserve and assign the most suitable safe spot to a CAV once it receives a take-over request. Additionally it adjusts the available lead time so that a CAV can at least prolong its automated driving mode in order to reach the assigned safe spot in case a MRM action is triggered. Although this lead time extension is part of Service 4, it also alters the overall TOR distribution of Service 5. We explain these implications and the other components further below.

Modification for distributed TOR advices

If a TOR advice is sent based on heuristic (a), the given lead time t_{lead} is tailored to match the estimated distance covered in case of a MRM to the next reachable safe spot. This means, t_{lead} is conceivably extended above the minimum value deriving from heuristic (a) to assure that a vehicle can reach a safe spot and avoid a full stop on the rightmost lane. The TMC prioritises the possible safe spot reachability over the distribution calculus.

When a TOC advice is sent and t_{lead} set to a new value, we fix the safe spot assignment and send the respective message in the same time step.

Safe spot assignment

For each time point t, each CAV k in automated mode, and each reachable safe spot i, there exists a probability $P_t(k,i)$ that, if k is assigned to use safe spot i (in case of a MRM), this safe spot will be occupied at arrival. We assume the most important determinant for P to be the number of vehicles n_i, which could all possibly use i for parking, between the reference CAV and the safe spot i . We also assume that the parking probability is of a larger order than the probability for a MRM, i.e. $P_{parking} \gg P_{MRM}$. To represent the influence of the number of vehicles normalised between 0 and 1, we define N_i as:

[3] x_1 is the calculated position, where a ToC should take place. Service 5 with its strategy for TOR distribution has been described in great detail in D4.2/1st. We refrain from more detailed explanations of service 5 here.

$$N_i = e^{-\frac{1}{n_i}}, \text{ where } 0 \leq N_i \leq 1.$$

Therefore, in case of free capacity $c = 1$:

$$P_t(k,i) \approx P_{parking} * N_i,$$

capacity $c = 2$:

$$P_t(k,i) \approx P_{parking}^2 * N_i * (N_{i-1}),$$

capacity $c = 3$:

$$P_t(k,i) \approx P_{parking}^3 * N_i * (N_{i-1}) * (N_{i-2}).$$

Note that the smaller the number of vehicles (and consequently N_i) between the reference CAV and the safe spot is, the closer the safe spot is to the reference CAV (at least when assuming identical capacities for all safe spots).

To avoid that the furthermost safe spots in front of the No-AD entry are used first, the distance driven in automated mode Δ_i (before a TOR advice is sent) is also included in the decision process. In general, the following five actions will be taken.

A. For each CAV k, a score related to the parking accessibility of each safe spot i is determined as below.

$$S_i = \alpha * \Delta_i - P_t(k,i)$$

The safe spot with the maximal S_i will be reserved to the respective CAV. (Note: This reservation is done internally within the traffic management logic. No information is communicated to the CAV, yet. Also, the parameter α serves to normalise Δ_i relative to the probability $P_t(k,i)$. The score S_i ranges between $[-1; 1]$.) The tentative assignment is updated within each traffic management step.

B. To ensure that the CAV can access the currently reserved and designated safe spot, it is examined if this selected spot can be reached when performing a ToC with a maximum ToC lead time till the vehicle comes to standstill. Also, it is checked if a nearby safe spot may be too close to access even by performing a MRM.

C. If a safe spot is in reach and the CAV exceeds its TOR position x_1 designated by Service 5, t_{lead} is tailored so that the CAV can stop on its designated safe spot in time. This requires an estimation about the prospective deceleration of the CAV based on the current traffic state (e.g. time gap and speed difference to leading vehicle) in order to prolong or shorten t_{lead}.

D. The reservation is then fixed. A TOR advice and a safe spot assignment will be sent to the CAV. The CAV caches this assignment internally and either successfully performs its ToC in time or, if not so, targets the assigned safe spot position when performing its MRM maneuver.

E. The TMC updates the information about the driving status of the respective CAV continuously and eliminates it from its assignment list when the CAV successfully performed its ToC, either in time or after arriving at its safe spot position.

A visualisation of these principal steps of services 4 algorithm is shown in Figure 108 in form of a flow chart.

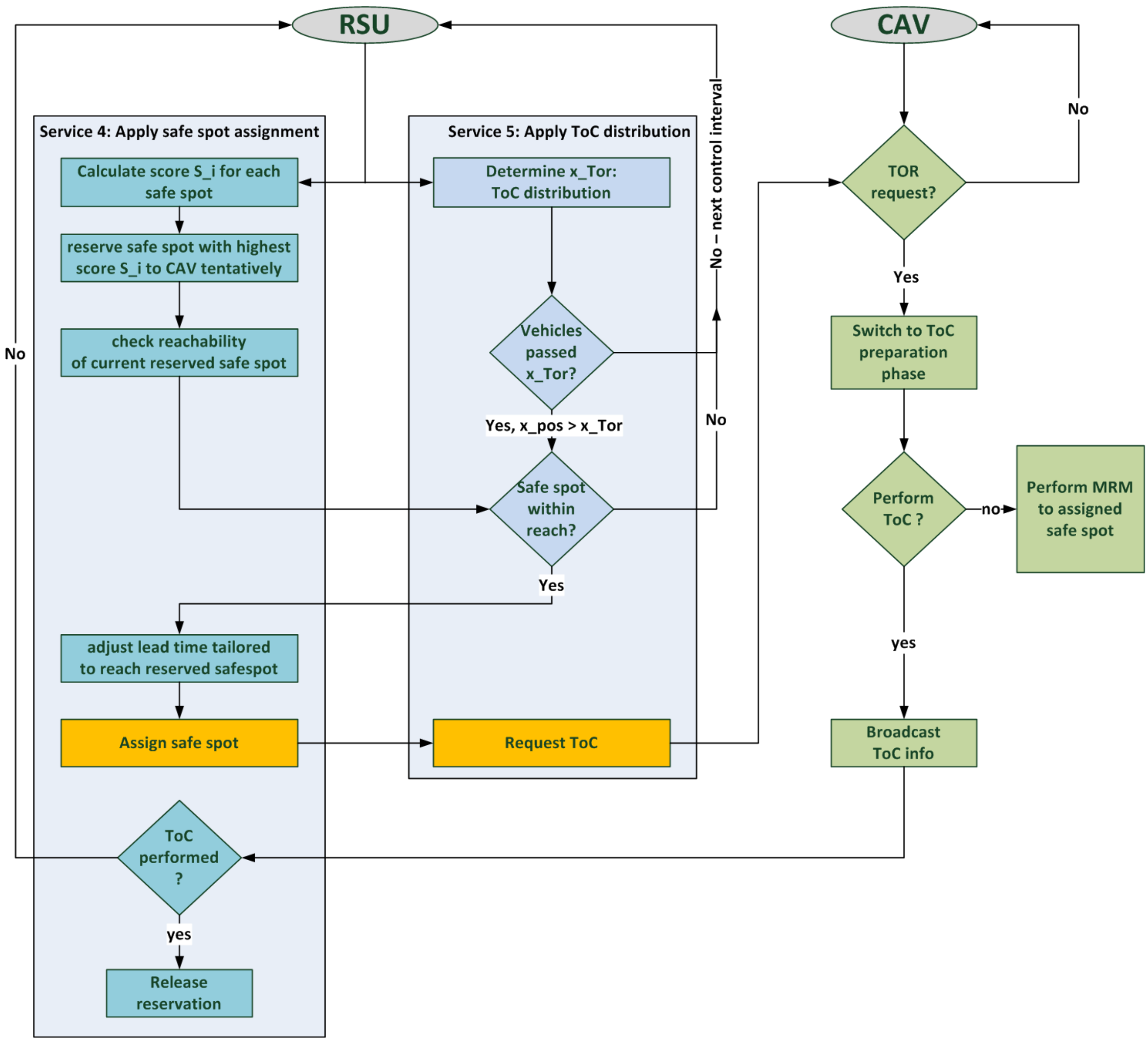


Figure 108: Flow chart of the traffic management application for UC45

Timeline of actions

1. RSI continuously monitors:
    a. the CAVs entering approach zone ahead of the No-AD zone,
    b. the occupancy state of the safe spots alongside the approach zone, and
    c. the traffic density in the approach area.
2. CAVs continuously send their current positions and driving mode status (‘automated’ or ‘manual’)
3. RSI continuously evaluates the traffic state for TOR distribution and safe spot reservation:
    a. If CAVs passes a specific position x_{TOR} and the respective reserved safe spot is within reach, the RSI sends a TOR and a safe spot assignment message.
4. CAVs that received a TOR, enter the ToC preparation phase. They also cache their assigned safe spot internally:
    a. If the human driver successfully takes over control of the vehicle in time, the CAV does not enter the MRM phase and informs the RSI about its ToC status (vehicle now driven ‘manually’). The RSI then releases the safe spot assignment internally.

   b. If the human driver does not take over control in time, the CAV enters the MRM phase and targets the cached safe spot received via the safe spot assignment message. It also tries to switch to the rightmost lane if it is driving on the left lane.
5. The CAV then either:
   a. enters the safe spot successfully or
   b. stops next to the targeted safe spot. Depending on the current traffic state this stop could result from dynamic parking behaviour when another vehicle spontaneously enters the parking slot before the CAV arrives at its assigned position OR if the CAV cannot successfully switch to the rightmost lane to enter the safe spot.
6. Once the CAV has successfully performed the ToC or left its safe spot, the RSI releases the CAV from its internal reservation list and lists the safe spot as available again.

3.2.5.2.2 CAV behaviour

In order to represent a safe spot assignment message, which will be part of the future MCM message definition currently in development by WP 5, we extended the current TOC model definition in SUMO by two additional parameters:

1. *mrmSafeSpot*
2. *mrmSafeSpotDuration*

By sending the first parameter *mrmSafeSpot* as an ID of a parking place, which corresponds to a target position, via TraCI, the TOC model caches this ID internally and forwards it as a ‘parking stop’ to SUMOs vehicle model when the CAV starts performing a MRM manoeuvre. The CAV consequently behaves as if it would have received a target position matching the safe spot position. The second parameter *mrmSafeSpotDuration* is optional for setting the stop duration within the designated parking position corresponding to the driver’s actual response time. As a default it is set to *60 seconds*.

3.2.5.2.3 Baseline scenario adaptation

To clearly showcase the impact of a MRM manoeuvre on traffic flow, for the baseline simulations in D3.1/2nd, we defined a solitary vehicle “MRM_01” with a prolonged response time of *200 seconds,* which consequently fails to perform a ToC and issues a MRM manoeuvre on the rightmost lane. The local impact of this vehicle “MRM_01” especially on traffic efficiency was clearly illustrated and its contribution to bad KPI performances was identified and discussed as well.

In order to showcase the capabilities of the newly developed Service 4, we adapt the baseline definition and add more “MRM” vehicles to the traffic flow. After *60 seconds* we insert a “MRM” vehicle every *5 minutes* with a driver response time of *60 seconds.* In total we add 12 “MRM” vehicles per seed into the traffic flow.

We expect these extra “MRM” vehicles to have a significant impact on the KPIs which should worsen notably compared to simulations depicted in D3.1/2nd. We reran the baseline simulations with these newly adapted “MRM” vehicle insertions for comparisons to the KPIs in presence of Service 4.

Table 18 summarises the network information used for the baseline and traffic management simulations (Note: No changes were made compared to D3.1/2nd iteration).

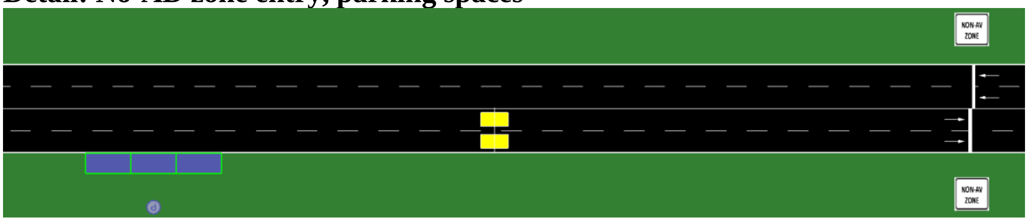
Table 18: Network configuration details for Scenario UC 4.1-5

UC4.1_5	Settings	Notes
Road section length	1.82 km	
Road priority	-	
Allowed road speed	13.89 m/s	• 50 km/h
Number of nodes	6	• n0 – n5
Number of edges	5	•
Number of O-D relations	1	• from n0 to n5
Number of lanes	2	• per direction
NoAD zone location	from n2 to n3	• length: 250 m, disallowed vClasses: custom1/2
Parking facilities	Located along edge “approach”	• five parking areas, equidistantly distributed at 150m. distance
Filenames	• network: UC45.net.xml • visualisation: view.xml • parking facilities: UC45.add.xml	

Intended control of lane usage
The section named “NO-AD” is not allowed to be entered by automated vehicles. Therefore TMC provides this information to approaching CAVs. Vehicles are free to choose lanes. The CAV inserted at minute 30 uses the rightmost lane.

Network layout

Detail: No-AD zone entry, parking spaces



Road segments
“entry” (n0→n1): Insertion area (100 m)
“approach” (n1→n2): Approaching area with parking places (870 m)
“NoAD” (n2→n3): NO-AD zone (250 m)
“upward” (n3→n4): Area for upward transitions (500 m)
“exit” (n4→n5): Leaving area (100 m)

3.2.5.3 Results

The impact of the proposed traffic management logic on traffic is analysed with the selected KPIs and compared with the baseline simulation results in the following sections respectively.

3.2.5.3.1 Impacts on traffic efficiency

Traffic efficiency will be analysed network-wide and locally as in the first iteration.

Network-wide impacts

Figure 109 shows in comparison to the baseline that the travel time average has been reduced in presence of the proposed traffic management logic especially when more vehicles enter the scenario and the share of CAVs is higher in the network. This mainly comes from instructing CAVs to target their assigned safe spots since Service 5 already distributes the ToCs along the approach area in both cases. Such safe spot target instructions prevent CAVs from disturbing the overall traffic flow within the approach area. We reason for the baseline simulation that, under such conditions, the smoothness of the traffic flow gets disrupted locally from consecutive severe MRMs which sometimes lead to situations where traffic flow hardly recovers for a longer period of time. These negative effects almost vanish and traffic flow remains rather smooth and undisturbed when applying Service 4. The vehicular lead time adjustment also enables CAVs to travel longer in automated mode until they reach their appointed safe spots. This helps to prevent bottleneck formation in the approach area in combination with Service 5. Figure 109 also shows that the overall travel time average remains quite constant for the traffic management case regardless of the parameter combination (LOS/Mix) and is probably quite near the travel time at free flow speed.

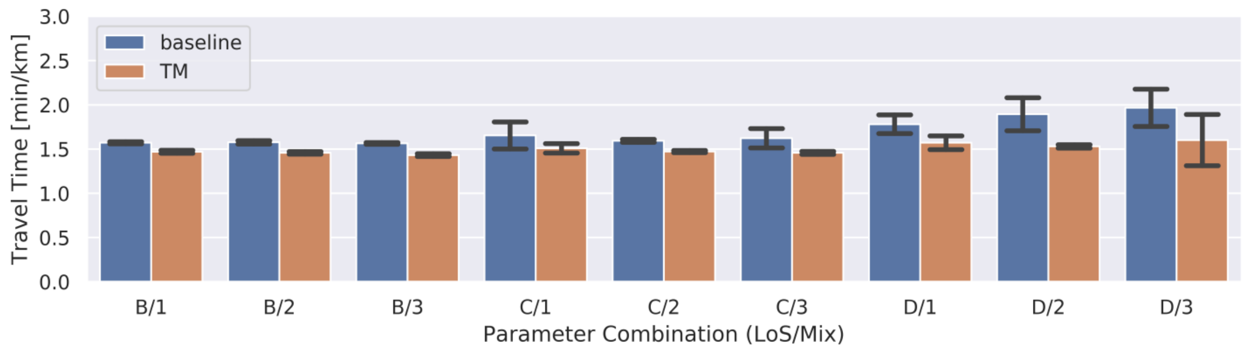


Figure 109: Travel time [min/km] for use case 4.1-5 simulation experiments (varying LOS and vehicle mix).

Local impacts

In general, when overserving the time-space diagrams in Figure 110, Figure 111 and Figure 112, it can been seen that for higher traffic demands and mixes the interference of severe MRM maneuvers both in speed and in flow is reduced by applying Service 4 (right panels) when comparing to the baseline case (left panels). The respective reduction becomes quite clearer and more obvious in denser traffic states when local disruptions can be eliminated with the adaption of the traffic management logic.

Firstly, Figure 110 exemplarily illustrates for the situation at LOS B with a low share of CAVs that disruptions by severe MRM manoeuvres only cause local disruptions (see panel (a) – light blue spots, panel (b) – areas almost without light blue spots), which quickly dissolve under these moderate traffic conditions. A comparison to the traffic management case indicates that variances in traffic flow (see panel (c) – few light blue spots, panel (d) – few dark blue areas) also occur due to casual parking activities and ToCs within the approach area. Nevertheless, differences between the baseline and TM case are rather small.

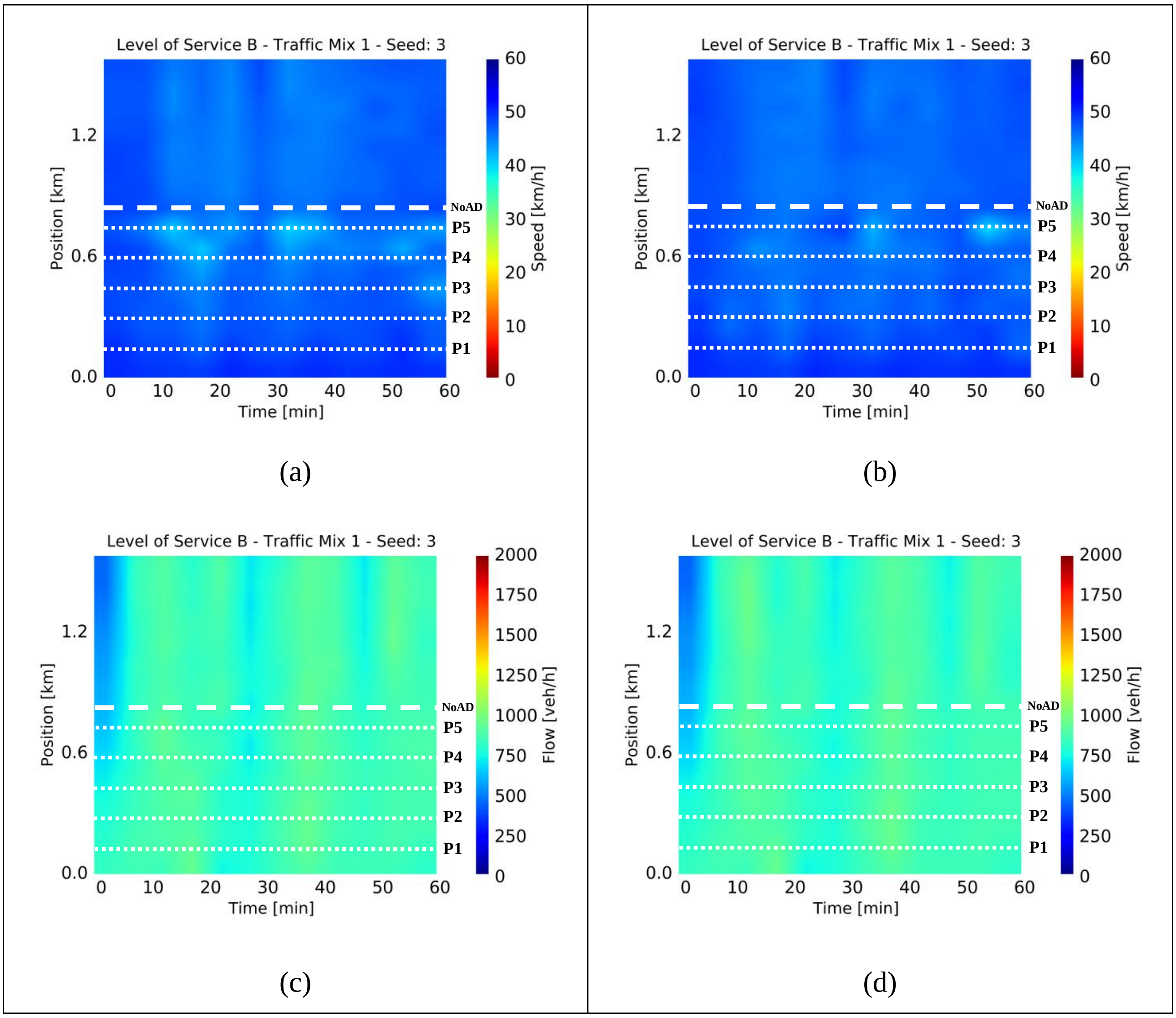


Figure 110: Exemplary time-space-diagrams for measured speed (upper row, panels (a) and (b)) and flow (bottom row, panels (c) and (d)) for use case 4.1-5 in comparison between baseline (left) and traffic management (right) for LOS B – vehicle mix 1 – seed 3. Thick white dashed lines indicate the entry position of the NO-AD zone, while thin white dashed lines mark the safe spot positions.

Regarding the traffic situation at LOS C with vehicle mix 2 the comparison of the panels (left vs. right) in Figure 111 shows to some extent the increasing impact of MRMs on speed and flow within the approach area, whereas these negative effects almost disappear in presence of Service 4's traffic management logic. Local disruptions occur as part of the overall scenario parking behaviour as well as due to MRM maneuvers (overall flow in panel (c) doesn't show notable differences to panel (d) whereas overall speed shows some local decline in panel (a) compared to (b)).

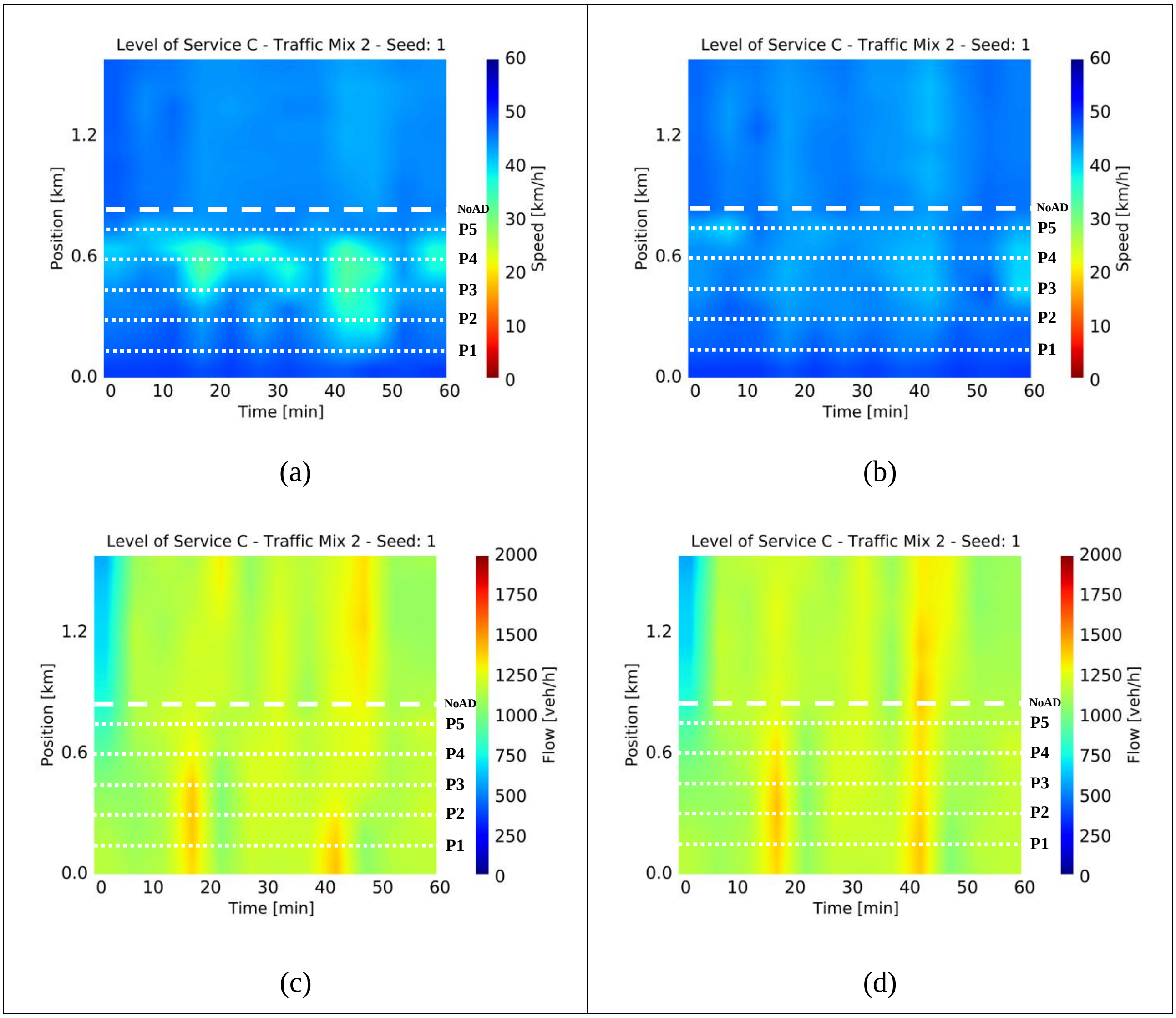


Figure 111: Exemplary time-space-diagrams for measured speed (upper row, panels (a) and (b)) and flow (bottom row, panels (c) and (d)) for use case 4.1-5 in comparison between baseline (left) and traffic management (right) for LOS C – vehicle mix 2 – seed 1. Thick white dashed lines indicate the entry position of the NO-AD zone, while thin white dashed lines mark the safe spot positions.

For the highest LOS and vehicle mix (LOS D / Mix 3), Figure 112 shows even stronger disruptions in traffic flow and speed, compared to Figure 111. Panel (b) and (d) illustrate that, under these conditions, local disruptions by severe MRMs become more impactful even in presence of the traffic management and do not dissolve as quickly when demand is as high as in LOS D. The light green spot in panel (b) at around minute 10 indicates a solitary MRM manoeuvre which causes a drop in overall speed, whereas panel (a) shows that at least several MRMs prolong such speed decrease (the yellow spots from minute *10* till *60* in panel (c)). A comparison of panel (c) and (d) indicates some lightly increased overall flow for the traffic management case although local disruptions are still part of the overall scenario behaviour.

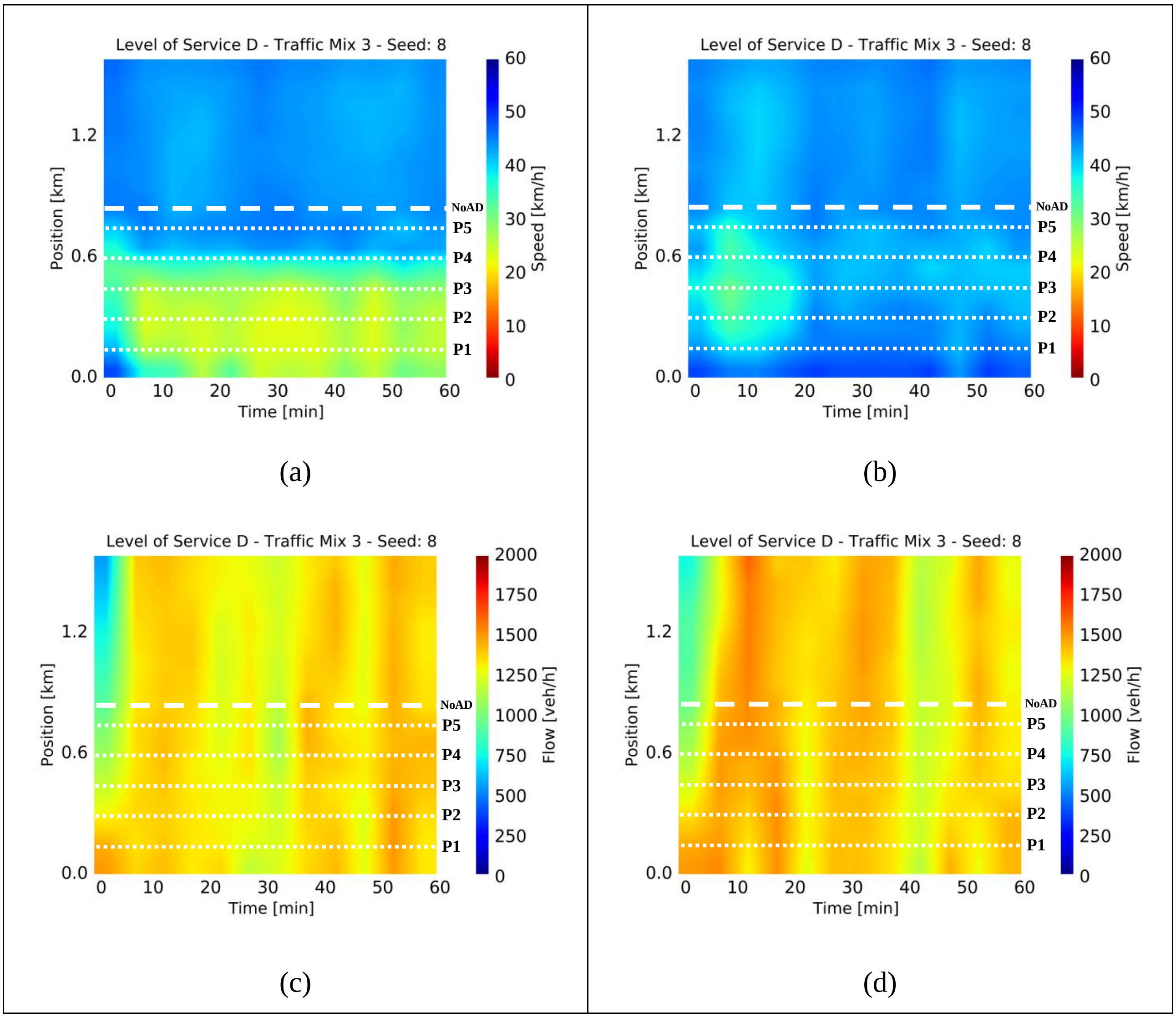


Figure 112: Exemplary time-space-diagrams for measured speed (upper row, panels (a) and (b)) and flow (bottom row, panels (c) and (d)) for use case 4.1-5 in comparison between baseline (left) and traffic management (right) for LOS D – vehicle mix 3 – seed 8. Thick white dashed lines indicate the entry position of the NO-AD zone, while thin white dashed lines mark the safe spot positions.

3.2.5.3.2 Impacts on Traffic Dynamics

The impact of the traffic management logic adaption on traffic dynamics is examined according to the changes in traffic throughput and the number of lane changes. The comparisons in Figure 113 and Figure 114 show that only small differences exist between the simulation results with and without traffic management, although the throughput in the traffic management case is slightly increased, particularly in denser traffic states, and the number of lane changes is slightly reduced. The former one corresponds to the above mentioned overall travel time results. The reason for the later one is that when less severe MRM performances occur, other road participants also need to make less lane changes for overpassing these stopping vehicles.

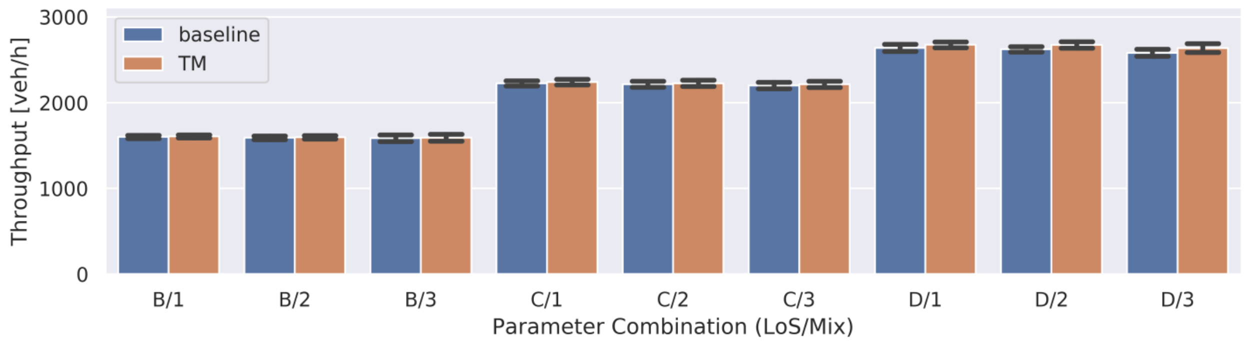


Figure 113: Throughput [veh/h] for use case 4.1-5 (varying LOS and vehicle mix).

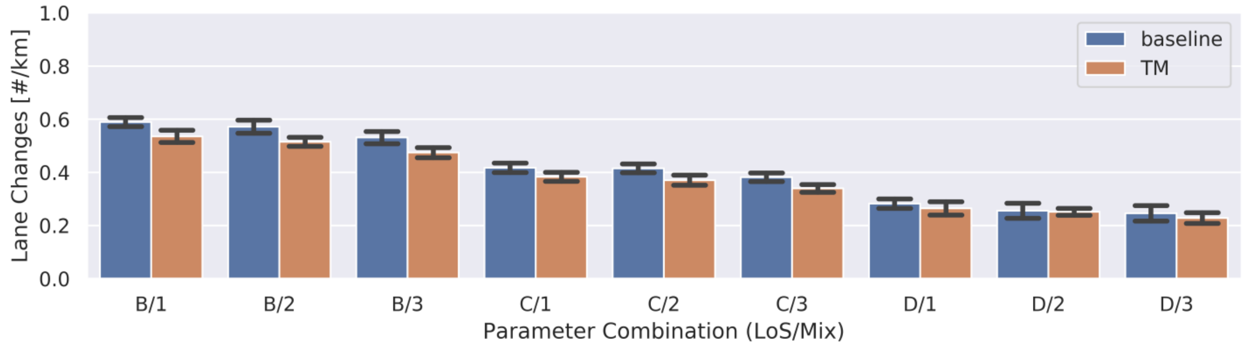


Figure 114: Number of lane changes per kilometre [#/km] for use case 4.1-5 (varying LOS and vehicle mix)

3.2.5.3.3 Impacts on traffic safety

In the second iteration traffic safety is analysed network-wide and also locally.

Network-wide Impacts

For evaluating traffic safety the time to collision is used. When it is less than *3 seconds*, it is recognised as a critical event. We observe in Figure 115 that the presence of Service 4 strongly improves traffic safety for all parameter combinations. Since severe MRMs on the road mostly vanish due to the safe spot assistance, heavy braking manoeuvres by following vehicles and also lane change induced TTCs decrease for the traffic management case. Therefore the number of TTCs only slightly increases with the LOS and vehicles mix when Service 4 is applied. (The trends for the baseline case were already explained in detail in D3.1/2nd.)

The above mentioned improvement degree depends mainly on the threshold definition of the critical event in the SUMO simulation, which might differ from the real world. Thus, different threshold values may affect the spectrum of the improvement range. In order to prove if these enhancements are robust to different parametrisation of the critical TTCs further respective investigations may help to clarify this interpretation quantitatively.

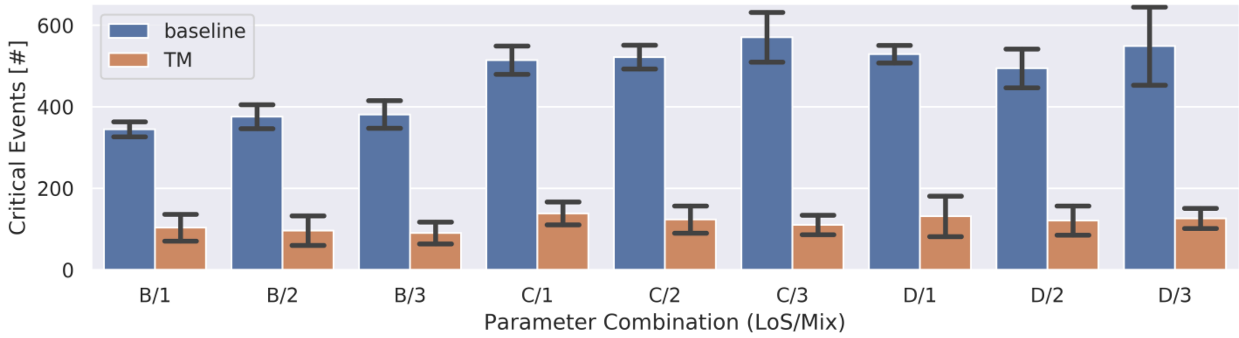


Figure 115, Average number of events with TTCs below 3.0 seconds for use case 4.1-5 (varying LOS and vehicle mix).

Local Impacts

With start of the second iteration we also analyze traffic safety locally. Therefore the locations of the events with TTC less than 3 seconds are plotted and analysed. Figure 116 shows the comparison of the spatial distribution of critical events exemplarily for LOS B with vehicle mix 2 between baseline (upper panel (a)) and traffic management (bottom panel (b)). The plots feature the aggregated number of critical TTCs of all seeds (per LOS/mix), marked as bins within the approach area. Each plotted bin means that at least one TTC occurred at this position. The color of a bin then indicates the amount of TTCs at this marked position. So, when e.g. several TTCs concentrate within a certain area, the colors can be considered as spatial density indicator for the interpretation of the TTC distribution.

When comparing the spatial distributions of critical TTCs at different LOS with different vehicle mixes, illustrated in Figure 116, Figure 117 and Figure 118, it is obvious that more critical events occurred close to the parking places (indicated as yellow and red bins) in the baseline simulations. This is mainly due to the interactions between the MRM vehicles and the vehicles, conducting parking activities (entering/leaving a parking space). Moreover, the ToC distribution of Service 5, adopted in the baseline simulations, takes the current traffic state into consideration when issuing ToCs. Thus, more critical events happened directly in front of the No-AD zone at LOS B due to the relative late ToC distribution made by Service 5. In denser traffic states, Service 5 issues ToC requests rather earlier. Thus, the critical events happen more distant from the No-AD zone (see the locations of the yellow and red bins in Figure 117 and Figure 118). The similar phenomenon can be found in the spatial distribution of lane changes. In addition, it can also been seen that some critical events also happen between two lanes when the lane changing actions are made. Such lane changing maneuvers are also obviously more often induced for the unmanaged cases, arguably because disruptions by MRMs cause following vehicles to switch lanes more often. In comparison to the aforementioned situations, the application of Service 4 has not only greatly reduced the conflicts between the MRM vehicles and the vehicles with parking activities (less bins around the parking area), but also avoided frequent lane changing behaviours, since CAVs can better manage their lane changing maneuvers with the given extended lead times.

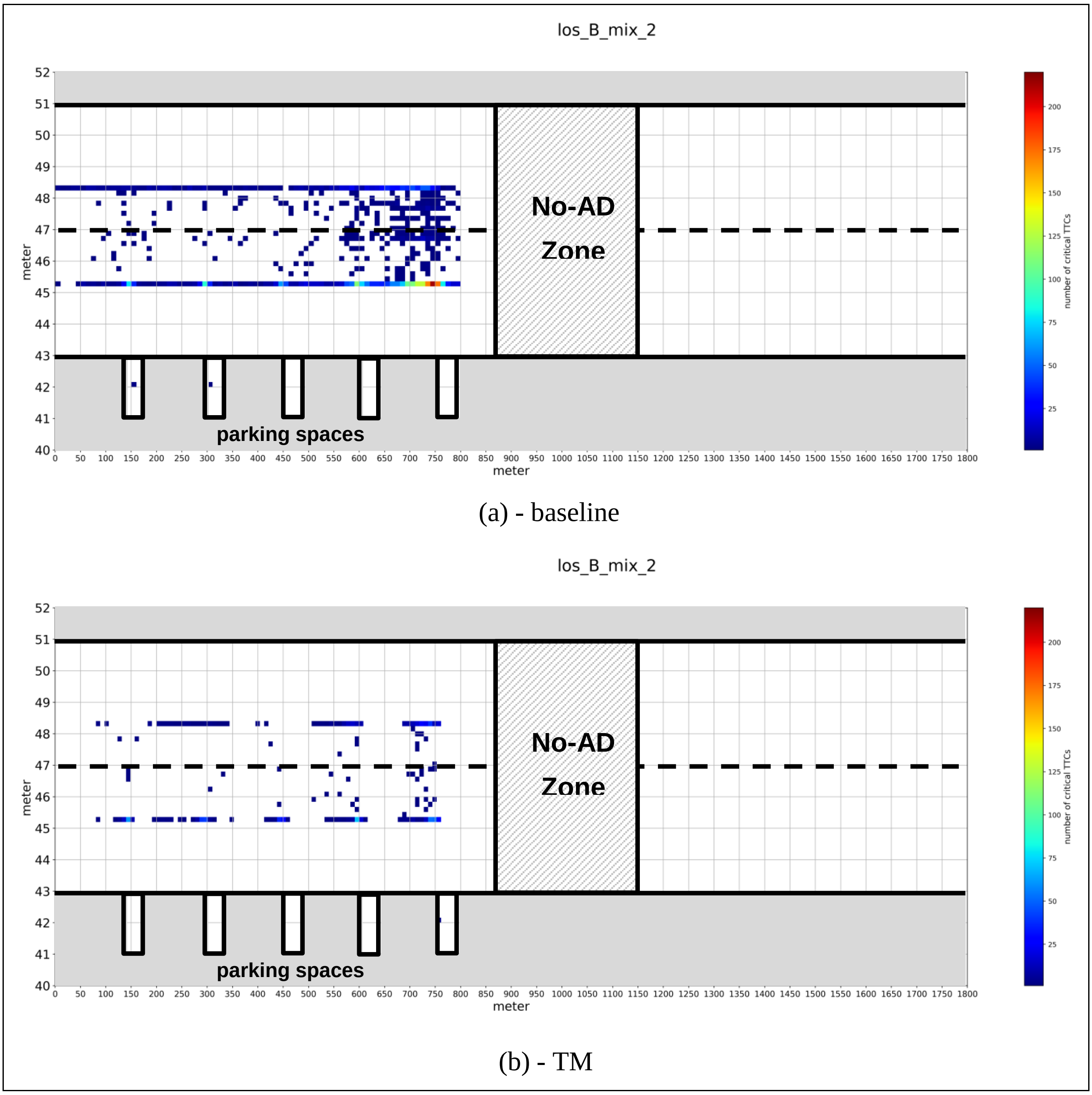
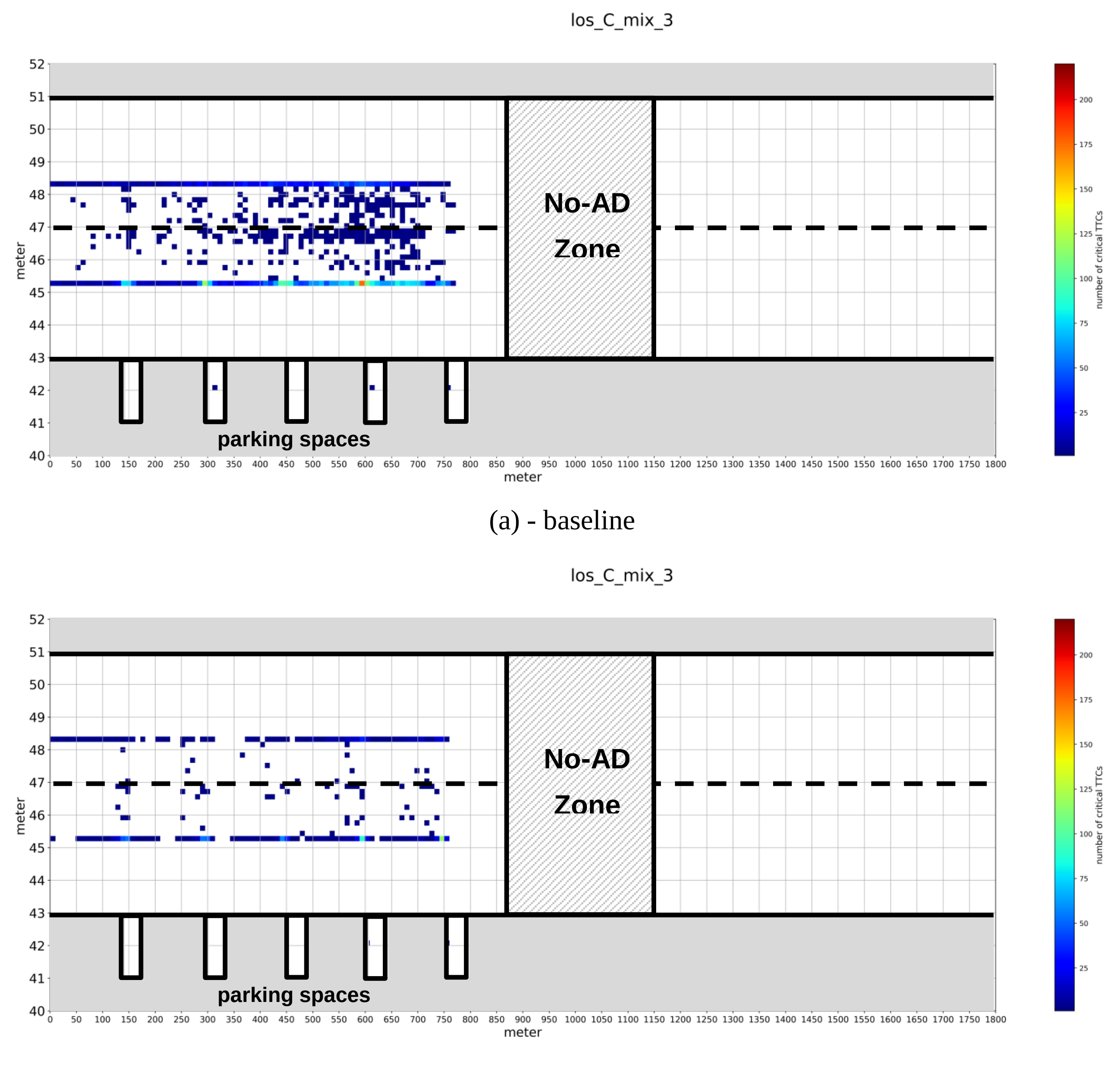


Figure 116: Spatial distribution of critical TTCs (< 3 sec) in comparison between baseline (upper panel (a)) and traffic management (bottom panel (b)) exemplarily for LOS B – vehicle mix 2. Colours indicate the number of critical TTCs shown with discrete plotted bins (bin size ≈ 20m x 0,3m).



(a) - baseline

(b) - TM

Figure 117: Spatial distribution of critical TTCs (< 3 sec) in comparison between baseline (upper panel (a)) and traffic management (bottom panel (b)) exemplarily for LOS C – vehicle mix 3. Colours indicate the number of critical TTCs shown with discrete plotted bins (bin size ≈ 20m x 0,3m).

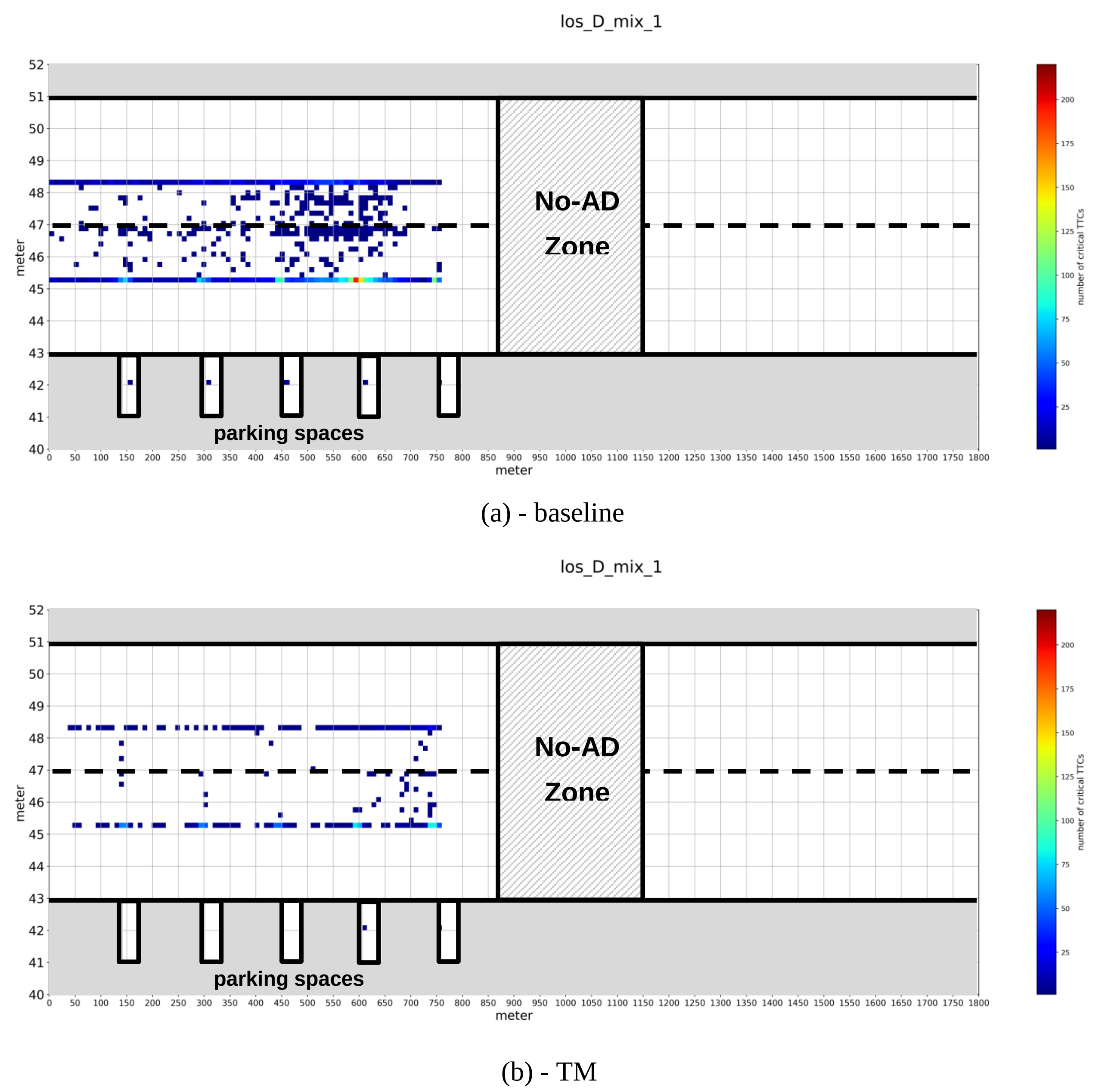


Figure 118: Spatial distribution of critical TTCs (< 3 sec) in comparison between baseline (upper panel (a)) and traffic management (bottom panel (b)) exemplarily for LOS D – vehicle mix 1. Colours indicate the number of critical TTCs shown with discrete plotted bins (bin size ≈ 20m x 0,3m).

3.2.5.3.4 Environmental impacts

When observing the comparison result in Figure 119, the proposed traffic management logic also contributes to the CO_2 reduction due to the improvement in overall travel speed and the less interference in traffic dynamics. Such contribution is more significant when the share of CAVs and the network density increases (see the results of C/3, D/2 and D/3 in Figure 119).

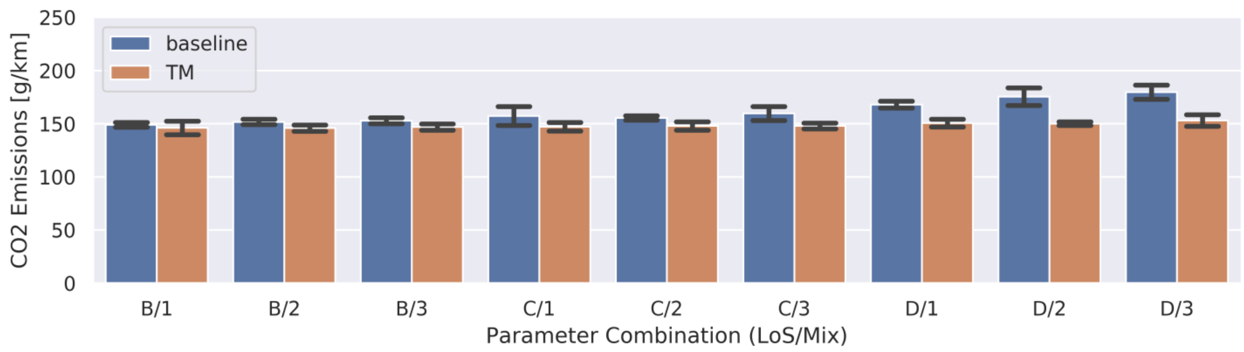


Figure 119; Average CO_2 emissions per kilometres travelled [g/km] for use case 4.1-5 (varying LOS and vehicle mix).

3.2.5.3.5 Metrics for Control Transitions

Figure 120 shows the number of TORs performed per LOS and vehicle mix. Expectedly, these numbers are identical for the baseline and traffic management case since every vehicle, equipped with a TOR device, is addressed by the traffic management application (i.e. CAVs receive a TOR and a safe spot assignment; CVs only receive a TOR).

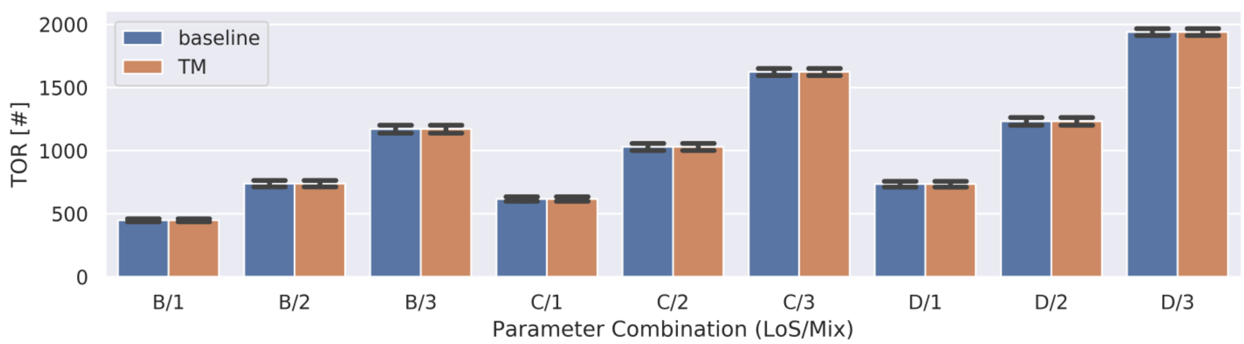


Figure 120; Total number of TORs for use case 4.1-5 (varying LOS and vehicle mix).

The following comparison for the number of performed MRMs, illustrated in Figure 121, is of great interest here because of the adjustments made on the ToC lead time t_{lead} by the traffic management logic as described in section 3.2.5.2.1. Due to the newly development functionality to adjust t_{lead}, we now observe an increased number of MRMs relative to the baseline simulation. Since the standard ToC lead time (*10 seconds*) is not static anymore and can be lower than this standard value, more drivers do not take over control before the remaining lead time expires[4]. As described in D3.1/2nd, baseline simulations are parameterised so that roughly 10% of all ToCs fail to succeed

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[4] Driver response times were defined and varied as part of the baseline definitions in WP3 via a Gaussian distribution and the pre-defined variance.

when t_{lead} reaches *10 seconds*. By shortening or extending t_{lead}, the traffic management logic now creates a distribution of ToC lead times depending on the current traffic state. This means that, in some cases, no MRM occurs because t_{lead} was extended when it would have t_{lead} staying at *10 seconds*. The same logic applies the other way around when shortening a ToC's lead time.

Interestingly, overall t_{lead} was more often shortened than it was extended, which is why the total number of MRMs increases up to almost 100% in the parameter combinations D/2 and D/3. Most of these MRMs are still relatively short since driver response times vary about *1 – 3 seconds* plus the newly added lead time.

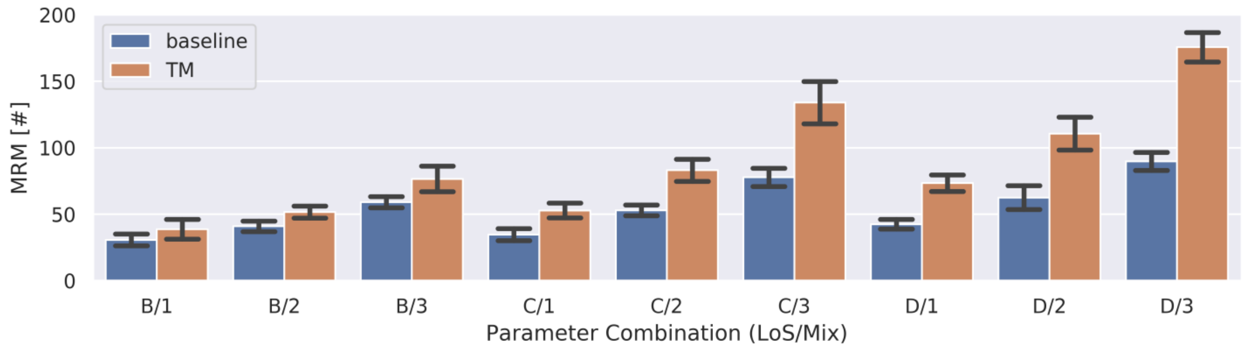


Figure 121; Total number of MRMs for use case 4.1-5 (varying LOS and vehicle mix).

3.2.5.4 Discussion

The simulation results show that the introduction of the proposed traffic management logic achieves overall improvements regarding all KPIs. Since traffic efficiency and emissions strongly correlates with each other, these similar improvements on these both KPIs are expected. For traffic dynamics, the related improvements are less obvious given the indicators 'throughput' and 'number of lane changes'. Nevertheless, with respect to the nature of the overall behaviour of this use case with spontaneous parking activities and serve MRM maneuvers, the enhancements, brought by Service 4, have great impact on the traffic system, which ultimately shows in the KPI traffic safety. This is conceivable, since the MRM vehicles make full stops directly on the road instead of on the safe spots in the baseline simulations. This is a highly safety-critical situation which makes the safe spot assistance so valuable.

When evaluating the performance of the safe spot assignment algorithm (Service 4) itself, it is revealed that the average miss rate is about 6.9%. This rate means that 6.9% of the MRM vehicles with prolonged driver response times cannot reach their appointed safe spots in time, although the spots are available and were assigned. The algorithm has to make several assumptions about the prospective deceleration rates of the respective CAV and its leading vehicles, because a ToC preparation phase and the subsequent MRM maneuver are always determined by a certain deceleration rate, based on the vehicle models' gap behaviours and the MRM parametrisation. These assumptions are necessary to determine the respective lead time adjustment in order to reach the assigned safe spot in an efficient manner. When the lead time adjustments are not accurate enough, CAVs might pass their assigned safe spots before coming to a full stop in most cases. Therefore, these predictions can be further improved to reduce the overall miss rate.

Due to the adjustment of ToC lead times, more MRM maneuvers appear in the traffic management case. Even so most of them are relatively short and therefore traffic safety is still greatly improved with the concern of the number of TTCs. Interestingly, the lead time adjustment results more often in shortened lead times than in prolonged ones. We suspect that this caused by the overall dynamic scenario behaviour. The scoring system S_i we applied is relatively volatile in respect to the current traffic state, which sometimes eventually leads to instantaneous switches of the discrete designated target positions corresponding to the safe spots. The reservation list is the basis for assigning safe spots when a TOR is issued by Service 5. When the reservation mechanism erratically causes a switch from a more distant safe spot to a closer one, adjusting t_{lead} is triggered a bit late by Service 5, which then results in shortened lead times. An investigation of the overall distribution of the lead time adjustments will be of interest for the future.

Moreover, the main objective of the current safe spot assignment logic is to provide the best suitable safe spot target given CAV's position, the current traffic state, and parking space availability. A free safe spot cannot be guaranteed in any case. Therefore some MRMs still occur on the road not only due to the capacity limitation of the safe spots, but also due to spontaneous real-life parking behaviour. Also it is more difficult for vehicles on the left lane to reach the assigned safe spot due to the necessary lane change maneuver while performing a MRM. When traffic is dense and vehicle composition is quite diverse between adjacent lanes, it often results in MRM stoppages on the left lane next to the assigned safe spot position because a timely lane change is not possible. The application of cooperative lane changing, which is currently under development in WP3, could help to reduce these undesirable situations.

Another possibility would be to develop a "keep-right advice" mechanism solely for CAV/MRM vehicles to start more far ahead of an upcoming No-AD zone before safe spot assignment services need to be applied. Accordingly, these advised vehicles would only induce disruptions on certain lanes next to their assigned, but unavailable, safe spots. In combination with Service 4, such an additional service could be helpful when there are many lanes on the road. In our use case, there are only two lanes, which is why we did not include such consideration in the TMC calculus as part of the traffic management logic and message service.

In conclusion, Service 4 in combination with Service 5 greatly improves the performances of all KPIs with the significant contribution of the safe spot assignment especially in regard of traffic safety, whereas Service 5 expectedly has proportionally greater impact on traffic efficiency and emissions as already indicated in the first iteration for simulations of use case 5.

4 Export traffic management measures for WP6

In the previous sections we discussed the performance of each of TransAID's traffic management Services individually. The next step, coinciding with Task 4.3 is to adapt these traffic management measures for the use in iTETRIS's integrated simulation platform, i.e. the iCS.

Whereas our current work was concerned with a preliminary simulation and evaluation of traffic management strategies, the next step will thus adapt these to be able to function in a more completed framework/setting as used in WP6. This requires looking at what can and/or will happen when a more complete picture of traffic flow is presented to the traffic management system. For example, the inclusion of specific communication features (as developed in WP5) is requiring the extension of the functionalities and range of the traffic management measures, so that they can take this into account and lead to a more performant traffic management system. We will then consider all these aspects, and reformulate the traffic management measures so that they can be used directly in WP6.

Further work could also focus on relaxing some of the implicit assumptions we made during the current assessments. For example, we assumed that all vehicle mixes and LOS are known a priori during configuration, so there was no explicit need for the TMC to detect it. In addition, we assumed the world is ideal, i.e. there are no uncertainties and we have perfect information regarding the present vehicle mix, the LOS, ... This could change by means of continuous state estimation, and even assess to what degree uncertainties (cf. distributions, probabilities, ... on the input) impact/deteriorate the system's performance.

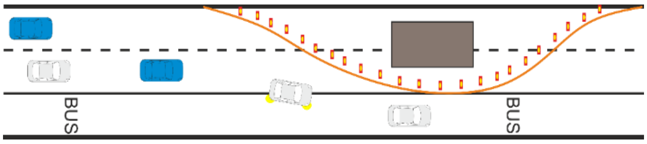
Before adding our traffic management services to WP6, we need to encode them in iCS's application layer, so that they will have a more orchestrated interaction with SUMO and ns-3.

5 Conclusions

This deliverable elaborated on ten of the previously selected use cases with respect to traffic management of automated driving at Transition Areas. To that end, the scenarios based on the use cases proposed by WP2 were used and adapted to consider various levels of scenario parameters (e.g., penetration of automation technology, traffic demand levels, and the lengths of the Transition Areas). The traffic management procedures developed in Task 4.1 were then implemented within the SUMO simulation environment. At this stage, we bypassed the detailed communication processing, and instead rely on basic (less complex) V2X interactions. This allowed the execution of various simulation runs and a rapid prototyping.

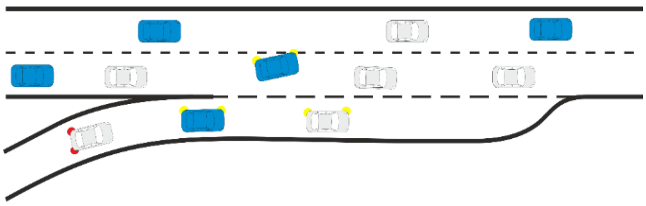
The initial proof-of-concepts of traffic management measures were implemented using the SUMO microscopic traffic simulator for a realistic representation of traffic, and the Python programming environment to code the traffic management procedures. They are calibrated and validated using predefined sets of KPIs/metrics. For each use case, we compare the cases with and without (i.e. base line) active traffic management measures. They are evaluated on their impacts on traffic efficiency (network-wide in terms of average speeds and throughput, and local in terms of tempo-spatial diagrams), traffic safety (by means of the number of events where a time-to-collision lower than 3 seconds occurred), and the environmental impacts (considering CO_2 emissions as calculated by SUMO's PHEMlight emissions model).

- **Service 1 (Use case 1.1): Prevent ToC/MRM by providing vehicle path information**



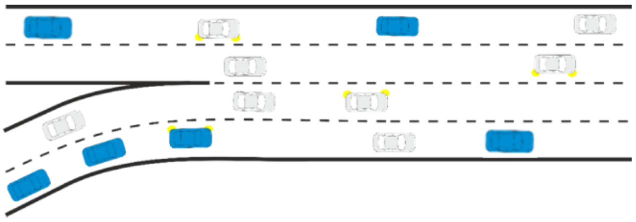
In the first service, path information was provided to AVs to circumvent road works via a bus lane. Simulation results indicated that overall traffic efficiency and CO_2 emissions remained unchanged, while traffic safety was improved significantly. Safety critical events were reduced ranging from 45% to 70%, depending on the level of service and traffic composition. The reduction was larger in case of less traffic and more AVs.

- **Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice**



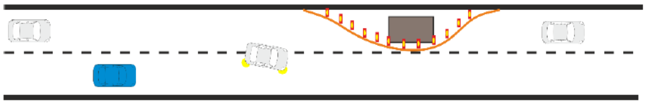
The second service was applied to a motorway merge area where AVs are given speed advice to merge onto the motorway. The service slightly increased average network speed and slightly decreased CO_2 emissions, especially in case of higher demand (LOS C). The impact on safety was more pronounced with a reduction of critical events around 75%.

- **Service 3 (Use case 3.1): Prevent ToC/MRM by traffic separation**



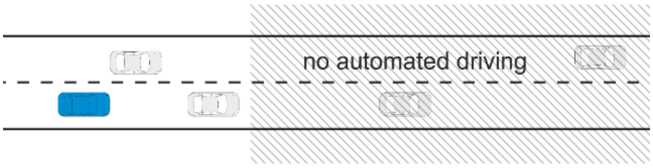
The third service was applied to a merging situation where two two-lane motorways merge into one four-lane motorway. The idea is to harmonise traffic by assigning the outer lanes to AVs, thereby reducing close interactions between non-automated vehicles and AVs in the merging area. Only in case of higher shares of AVs (> 25% level 2, > 25% level 3) in combination with LOS B or C, improvements were observed in throughput at the cost of slightly lower average network speeds and a decrease in safety. In short, rearranging traffic to dedicated lanes shows largely similar performance to 'uncontrolled merging' (i.e. no measures). However, we hypothesise that separating traffic can outperform uncontrolled merging when cooperative manoeuvring is applied.

- **Service 4 (Use case 4.2): Manage MRM by guidance to safe spot (urban & motorway)**



For Service 4 both an urban and motorway scenario were studied with similar network layouts. On a two-lane road we created safe spots upstream of a road works zone on the left lane for AVs to stop in case they reach the limit of their operational design domain. In this case the open right lane remains unblocked. As expected, traffic, safety and environmental benefits are realised. Only in case of congestion, when traffic is already moving slowly, the improvement diminishes.

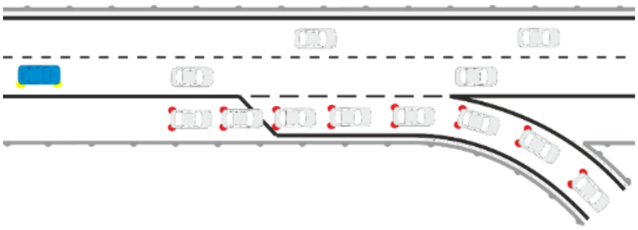
- **Service 5 (Use case 5.1): Distribute ToC/MRM by scheduling ToCs**



Finally, a no automated driving zone was simulated along the downstream part of a two-lane motorway for the fifth service. The zone can represent different situations (e.g., road works, geofences, weather, accidents, …) that prevent AVs from staying in automated driving mode. It is assumed that AVs increase their headway before handing over control to the driver. When this happens in a concentrated fashion just before the no-AD zone, traffic flow is impacted. We therefore distribute these handovers in time and space upstream of the zone. It was found that this service greatly smoothens out the disturbances caused by the handovers and improves traffic efficiency.

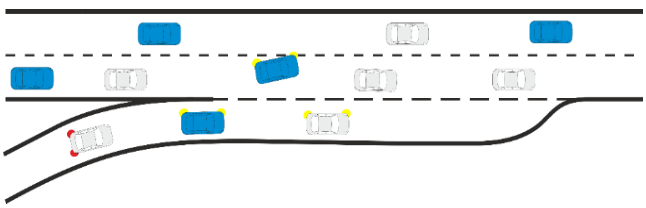
As explained in Deliverabe 2.2, we used the insights obtained during the first iteration to select five new use scenarios for the second iteration, adding new functionalities and providing overall improvements and/or extensions regarding vehicle modelling and cooperation. The newly selected use cases were:

- **Service 1 (Use case 1.3): Queue spillback at exit ramp**



In the first use case (queue spillback at exit ramp), the simulations with traffic management show a significant reduction of the queuing, especially on the main road. This has a beneficial effect on all indicators. The average travel time decreases, despite the speed limits applied in the traffic management scenario. The impact on the average travel time due to the extra capacity generated by opening the emergency lane for queuing exceeds the increase caused by the speed limits. The number of lane changes reduces as the LOS increases, the vehicle mix does not impact the number of lane changes significantly. The number of lane changes only slightly decreases from the baseline to the traffic management scenario. The throughput increases strongly between LOS B and LOS C in the traffic management scenario. There is no significant impact of the vehicle mix on the throughput. Compared to the baseline, the scenario with traffic management has a slightly higher throughput, especially for LOS C and LOS D. The average number of safety-critical events increases with the LOS and with the share of AVs in the vehicle mix, but it is still significantly reduced compare to the baseline. As LOS increases, queue length grows, and therefore speed differences and the occurrence of critical events both increase. AVs that can not find an appropriate gap in the queue to merge can stop on the main route for up to 10 seconds until they finally merge or finally reroute. These vehicles cause perturbations on the lanes of the main road, which can cause TTCs. CO_2 emissions increase slightly with the LOS and with the share of AVs in the vehicle mix. The queue length increases as the share of AVs increases in the vehicle mix. The CO_2 emissions correlate with the queue length, due to stop-and-go traffic in the queues.

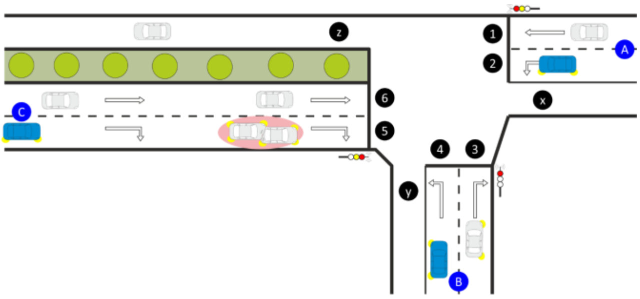
- **Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice**



For the second use case (preventing a ToC/MRM by providing speed, headway, and/or lane advice), we noticed that the inclusion of ramp metering (using the merging assistant system algorithm) improved the ToC percentage by means of gap searching, speed advice, and gap creating via pairing. In addition, the number of lane changes also decreased under the control logic as well as the variations between runs, showing improvement on homogeneity of traffic flow. There was a slightly negative impact of traffic efficiency and environmental impact, which could be correlated to the parameter settings of the merging assistant system and ramp metering configuration.

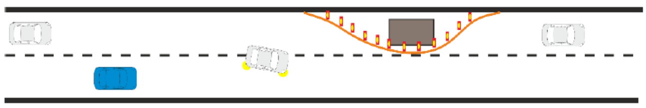
The control logic has strengthened safety objectives as one would expect. Less late merging and no end-of-the-acceleration-lane merging will happen, which could cost the performance of average travel time and average network speed, especially under heavier traffic demand due to lower capacity of the on-ramp. Thus, the merging assistant system and the intelligent ramp metering using this system shows the functional ability to prevent ToC and MRM. The trade-off between efficiency and ToC percentage is as expected for non-congested traffic situations. For congested traffic situations, ramp metering targeting lower ToC rates is not effective anymore because of expected increasing ToCs and MRMs of merging vehicles.

- **Service 2 (Use case 2.3): Intersection handling due to incident**



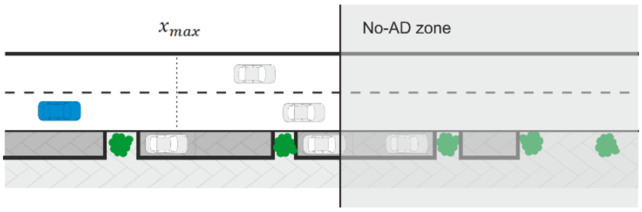
Looking at the third use case (intersection handling due to incident), we assumed that CAVs and CVs receive information about the incident itself (position, type, etc.), and will also receive a reduced speed advice and are able to use another lane to turn right. Due to an update timing plan where the traffic coming from the incident road gets extra green time, the saturation and travel times in the traffic management scenario are up until LOS D. In the LOS D simulations, the building up of the queue is more persistent en precedes downstream in time. The impact of the incident is nevertheless less severe in comparison to the Day 1 C-ITS simulations.

- **Service 4 (Use case 4.2): Safe spot in lane of blockage & Lane change Assistant**



In the fourth use case (safe spot in lane of blockage & lane change assistant), the simulation results for both the urban and motorway networks indicate that infrastructure-assisted traffic management and cooperative driving can generate traffic efficiency, traffic safety, and environmental benefits in the vicinity of Transitions Areas. CAV guidance to safe spots, lane advice (change/keep) provision from the RSI, and distributed cooperative manoeuvring reduce traffic disruption induced by MRMs in lane, dynamic TORs and non-homogeneous lane change behaviour in the proximity of lane drop bottlenecks (e.g., work zones). Specifically, reported results show that average travel time, shockwaves, lane change intensity, TORs, safety critical events, and CO_2 emissions reduce for Traffic Management scenarios, while throughput increases.

- **Service 4+5 (Use cases 4.1 and 5.1): Distributed safe spots along an urban corridor**

  Finally, the last combination of use cases (distributed safe spots along an urban corridor) showed that the introduction of the proposed traffic management logic achieves overall improvements regarding all KPIs. With respect to the nature of the overall behaviour of this use case with spontaneous parking activities and serve MRM maneuvers, the enhancements, brought by Service 4, have great impact on the traffic system, which ultimately shows in the KPI traffic safety. Due to the adjustment of TOC lead times, more MRM maneuvers appear in the traffic management case. Moreover, the main objective of the current safe spot assignment logic is to provide the best suitable safe spot target given CAV's position, the current traffic state, and parking space availability. A free safe spot cannot be guaranteed in any case. Therefore some MRMs still occur on the road not only due to the capacity limitation of the safe spots, but also due to spontaneous real- life parking behaviour. In conclusion, Service 4 in combination with Service 5 greatly improves the performances of all KPIs with the significant contribution of the safe spot assignment especially in regard of traffic safety, whereas Service 5 expectedly has proportionally greater impact on traffic efficiency and emissions as already indicated in the first iteration for simulations of use case 5.

We finally also provided a short description of how the output of this deliverable feeds into the next one (D4.3) and the integration work in WP6.

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7 Appendix A: Used traffic conditions and vehicle mixes

The ‘right’ traffic management measures are dependent on traffic conditions and the vehicle mix, as defined in deliverable D2.2 and updated in D3.1. The following tables were reproduced from those deliverables for reasons of clarity and completeness:

- Definition of the levels of service (LOS) A through C
- Overview of the different vehicle types, aggregated into classes of actors
- Artificial vehicle mixes for baseline simulations during 1st project iteration

Table 19: Vehicles/hour/lane for Level of Service A, B and C in urban, rural, and motorway conditions.

	LOS A	LOS B	LOS C
Urban (50km/h) – 1500 veh/h/l	525	825	1155
Rural (80 km/h) – 1900 veh/h/l	665	1045	1463
Motorway (120 km/h) – 2100 veh/h/l	735	1155	1617
Intensity / Capacity (IC) ratio	0.35	0.55	0.77

Table 20: Classification of actors (vehicle types).

Class Name	Class Type	Vehicle Capabilities
Class 1	Manual Driving	– Legacy Vehicles – (C)AVs/CVs (any level) with deactivated automation systems
Class 2	Partial Automation	– AVs/CVs capable of Level 1 and 2 automation – Instant TOC (uncontrolled driving in case of distracted driving) – No MRM capability
Class 3	Conditional Automation	– (C)AVs capable of Level 3 automation (level 3 systems activated) – Basic ToC (normal duration) – MRM capability (in the ego lane depending on speed and a predetermined desired MRM deceleration level)
Class 4	High Automation	– (C)AVs capable of Level 4 automation (automation activated) – Proactive ToC (prolonged duration) – MRM capability (in the rightmost lane depending on speed and a predetermined desired MRM deceleration level)

Table 21: Artificial vehicle mixes for baseline simulations during 1st project iteration.

Vehicle Mix	Class 1	Class 1 (Conn.)	Class 2	Class 2 (Conn.)	Class 3	Class 3 (Conn.)	Class 4	Class 4 (Conn.)
1	60%	10%	-	15%	-	15%	-	-
2	40%	10%	-	25%	-	25%	-	-
3	10%	10%	-	40%	-	40%	-	-