



D4.2

Preliminary simulation and assessment of enhanced traffic management measures

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Table of contents

Document revision history	2
Table of contents	4
1 Introduction	7
1.1 About TransAID	7
1.2 Purpose of this document	8
1.3 Structure of this document	8
1.4 Glossary	9
2 Traffic management measures per use case	11
2.1 Service 1 (use case 1.1): Prevent ToC/MRM by providing vehicle path information	11
2.1.1 Introduction	11
2.1.2 Traffic management setup	12
2.1.2.1 Traffic management logic	12
2.1.2.2 CAV behaviour	13
2.1.2.3 Baseline scenario adaptation	13
2.1.3 Results	14
2.1.3.1 Impacts on traffic efficiency	14
2.1.3.2 Impacts on traffic safety	18
2.1.3.3 Environmental impacts	19
2.1.4 Discussion	20
2.2 Service 2 (use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice	21
2.2.1 Introduction	21
2.2.2 Traffic management setup	23
2.2.2.1 Merging algorithm design	23
2.2.2.2 Traffic management zoning	28
2.2.2.3 Baseline scenario adaptation	31
2.2.2.4 Simulation scenarios set-up	32
2.2.3 Results	34
2.2.3.1 Impacts on ToC rate and vehicle stops	34
2.2.3.2 Impacts on traffic efficiency	39
2.2.3.3 Impacts on traffic safety	44
2.2.3.4 Environmental impacts	45
2.2.4 Discussion	46
2.2.4.1 Conclusion	46

2.2.4.2	Planned research for the 2 nd iteration.....	47
2.3	Service 3 (use case 3.1): Prevent ToC/MRM by traffic separation.....	50
2.3.1	Introduction.....	50
2.3.2	Traffic management setup.....	50
2.3.2.1	Description of the areas	50
2.3.2.2	Baseline scenario adaptation.....	52
2.3.2.3	Traffic separation logic.....	54
2.3.3	Results.....	58
2.3.3.1	Impacts on traffic efficiency.....	58
2.3.3.2	Impacts on traffic safety	62
2.3.3.3	Environmental impacts	63
2.3.4	Discussion	65
2.4	Service 4 (use case 4.2): Manage MRM by guidance to safe spot (urban & motorway)....	66
2.4.1	Introduction.....	66
2.4.2	Traffic management setup.....	66
2.4.2.1	Baseline scenario adaptation.....	66
2.4.2.2	Traffic management logic.....	67
2.4.2.3	CAV behaviour.....	68
2.4.3	Results.....	69
2.4.3.1	Urban scenario	69
2.4.3.2	Motorway scenario	75
2.4.4	Discussion	83
2.5	Service 5 (use case 5.1): Distribute ToC/MRM by scheduling ToCs.....	84
2.5.1	Introduction.....	84
2.5.2	Traffic management setup.....	84
2.5.2.1	TOR scheduling algorithm	85
2.5.2.2	C(A)V behaviour	89
2.5.2.3	Baseline scenario adaptation.....	90
2.5.3	Results.....	91
2.5.3.1	Impacts on traffic efficiency.....	91
2.5.3.2	Impacts on traffic safety	95
2.5.3.3	Environmental impacts	97
2.5.4	Discussion	98
3	Export traffic management measures for WP6.....	99
4	References.....	100

5 Appendix A: Used traffic conditions and vehicle mixes 101

1 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.

1.1 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.

1.2 Purpose of this document

In this document we elaborate on the five 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.

1.3 Structure of this document

This document follows a straightforward structure, in that we discuss each of the five selected traffic management services in turn in Section 2, as follows:

- Section 2.1: Service 1 (Use case 1.1): Prevent ToC/MRM by providing vehicle path information
- Section 2.2: Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice
- Section 2.3: Service 3 (Use case 3.1): Prevent ToC/MRM by traffic separation
- Section 2.4: Service 4 (Use case 4.2): Manage MRM by guidance to safe spot (urban & motorway)
- Section 2.5: Service 5 (Use case 5.1): Distribute ToC/MRM by scheduling ToCs

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 ends in Section 3 with a short description of how the output of this deliverable will feed into the next one (D4.3) and the integration work in WP6.

1.4 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-everything
VMS	Variable message sign

2 Traffic management measures per use case

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

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

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

2.1.1 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)V's 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)V's 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)V's 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)V's. 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)V's 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.

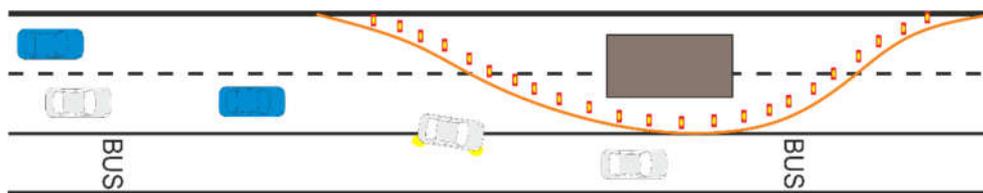


Figure 1: Scenario layout of use case 1.1.

2.1.2 Traffic management setup

2.1.2.1 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 function¹. 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.

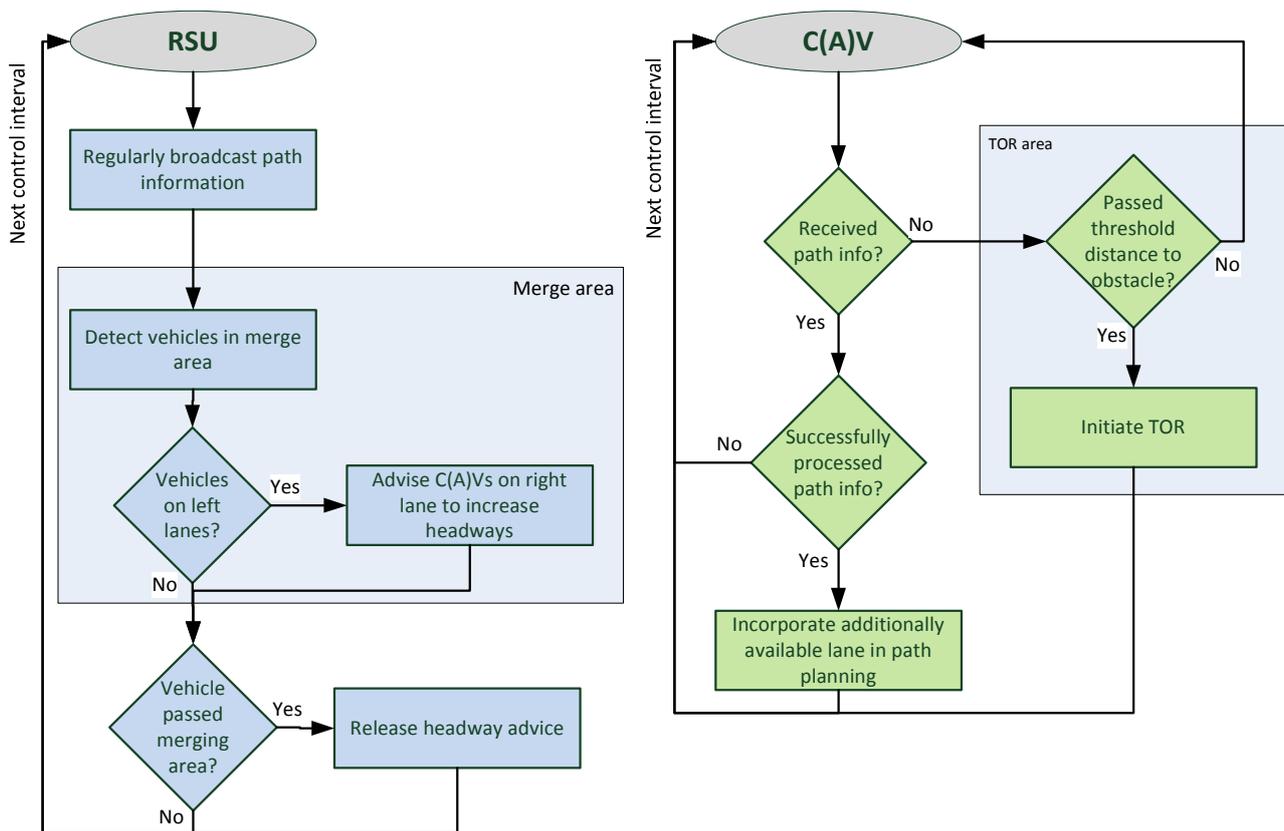


Figure 2: Traffic management logic of Service 1.

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.

2.1.2.2 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)V 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)V continue with their default headway settings.

2.1.2.3 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)V, 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.

2.1.3 Results

The performance of the proposed Service 1 is evaluated with respect to four aspects, i.e. traffic efficiency, traffic safety, and CO₂ emissions. The simulation results of the baseline simulations are used as reference for the performance evaluation.

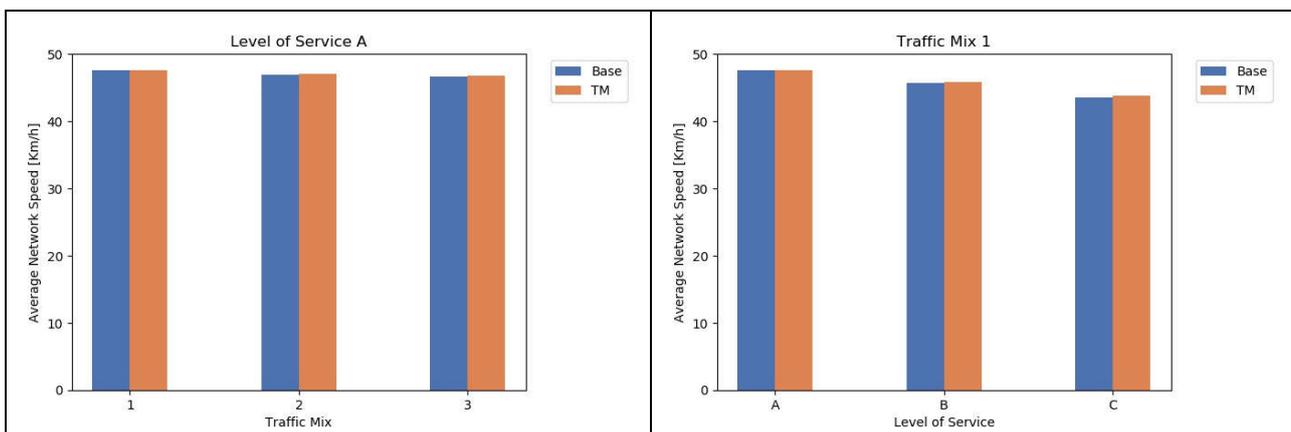
2.1.3.1 Impacts on traffic efficiency

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.



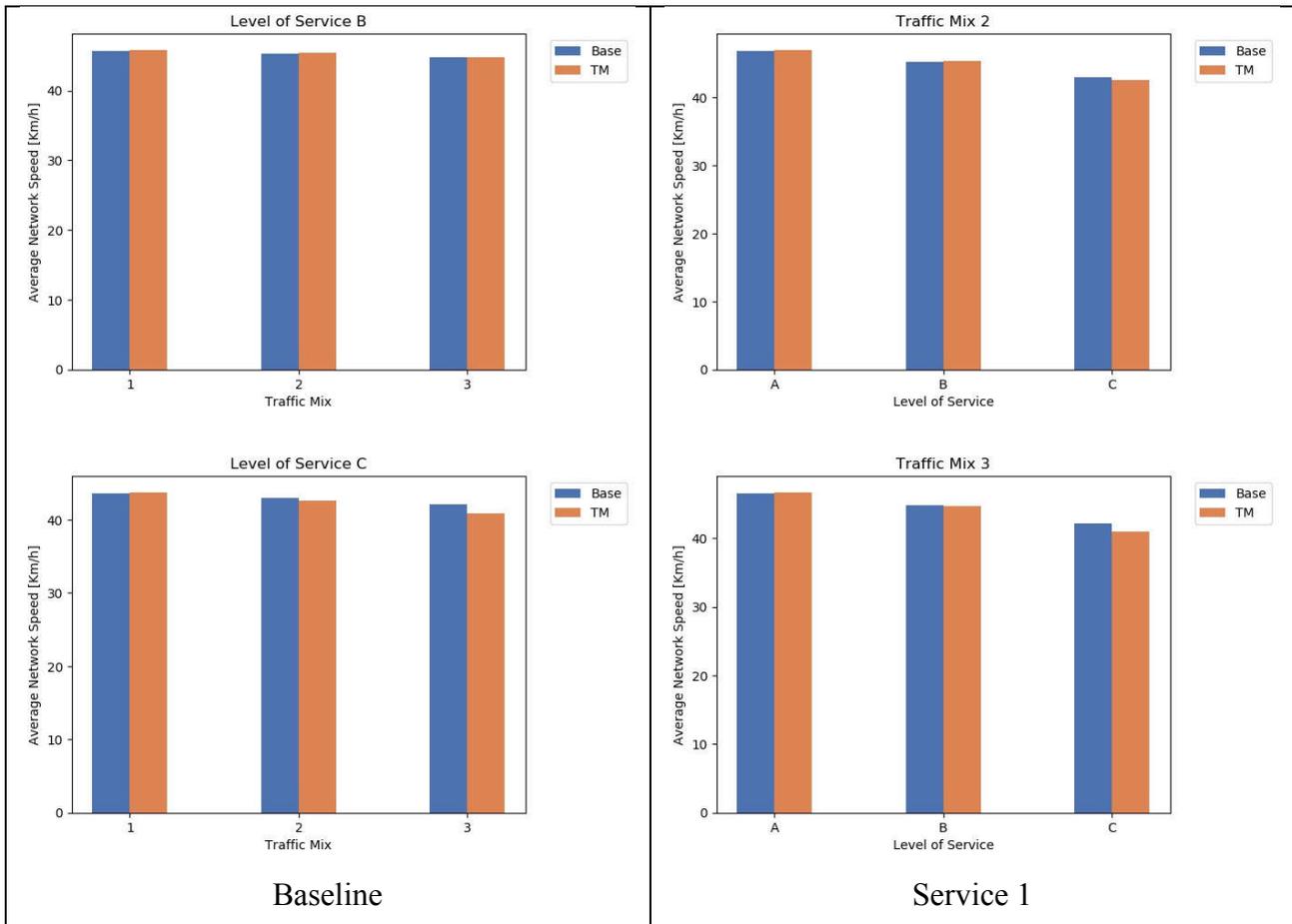


Figure 3: Average network speed for use case 1.1 (urban network) simulation experiments (varying the LOS and vehicle mix). Different bar colours correspond to baseline and traffic management simulations.

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.

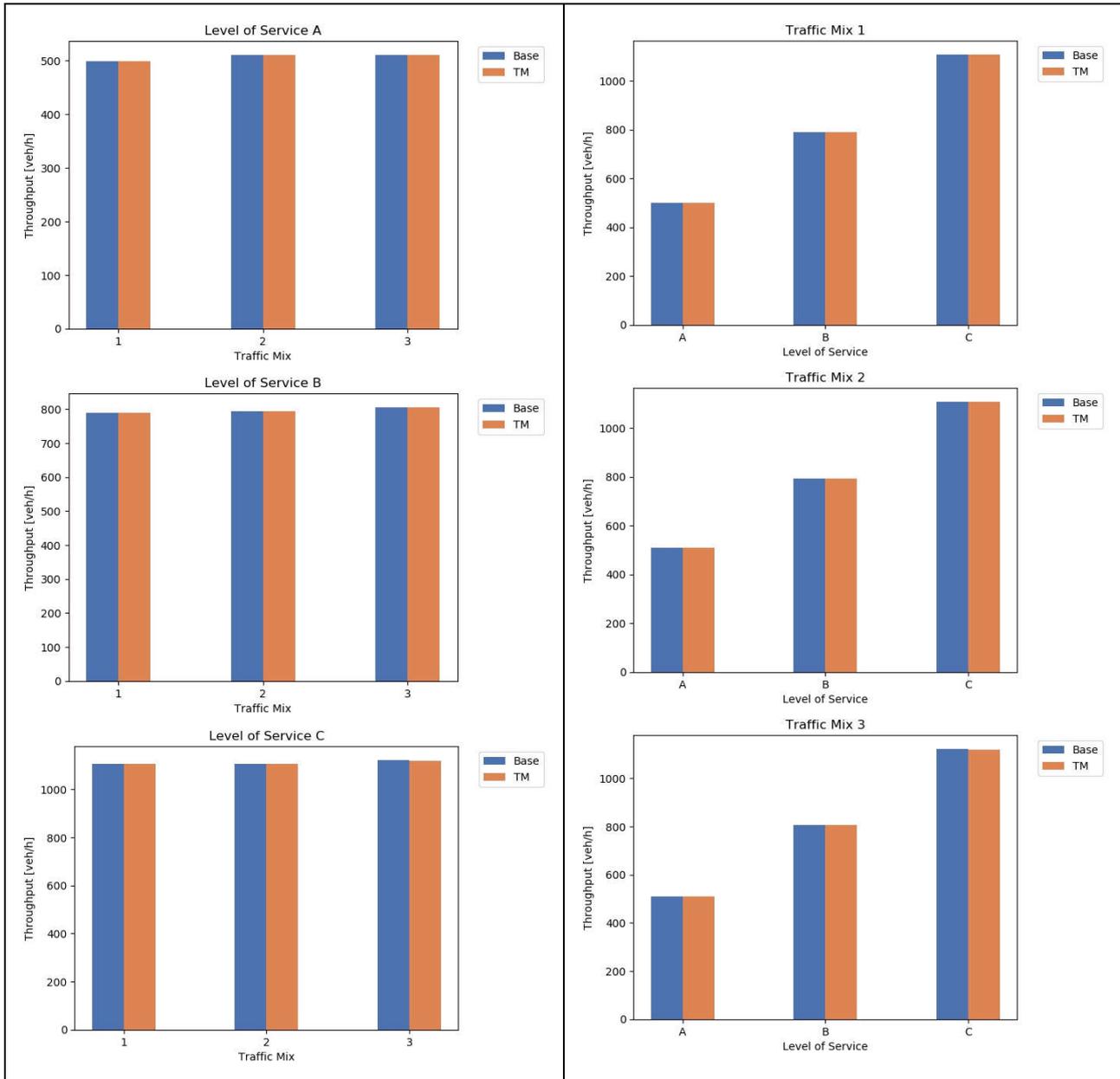


Figure 4: Throughput for use case 1.1 (varying the LOS and vehicle mix). Different bar colours correspond to the baseline and traffic management simulations.

Local Impacts

Similarly 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).

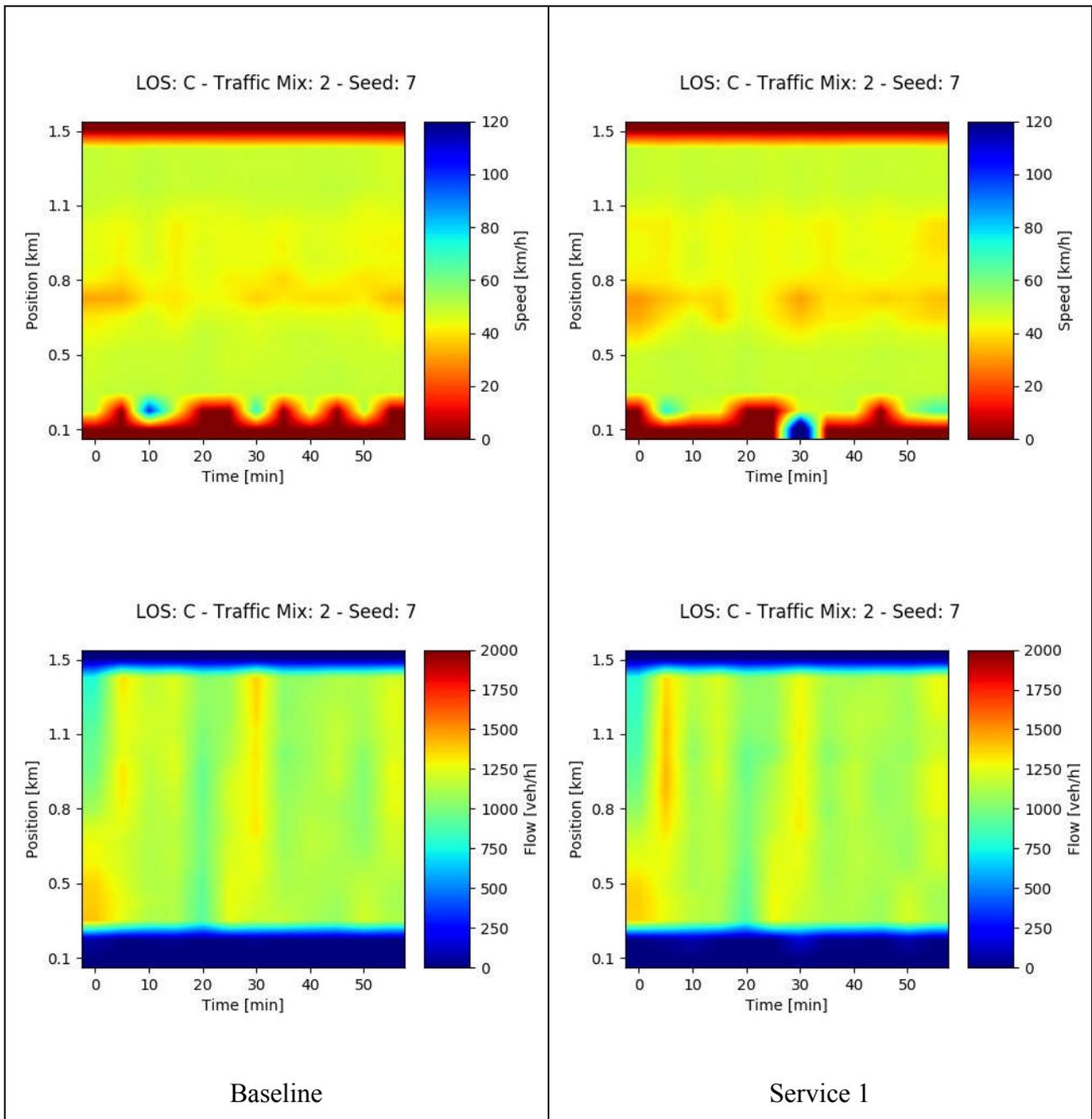
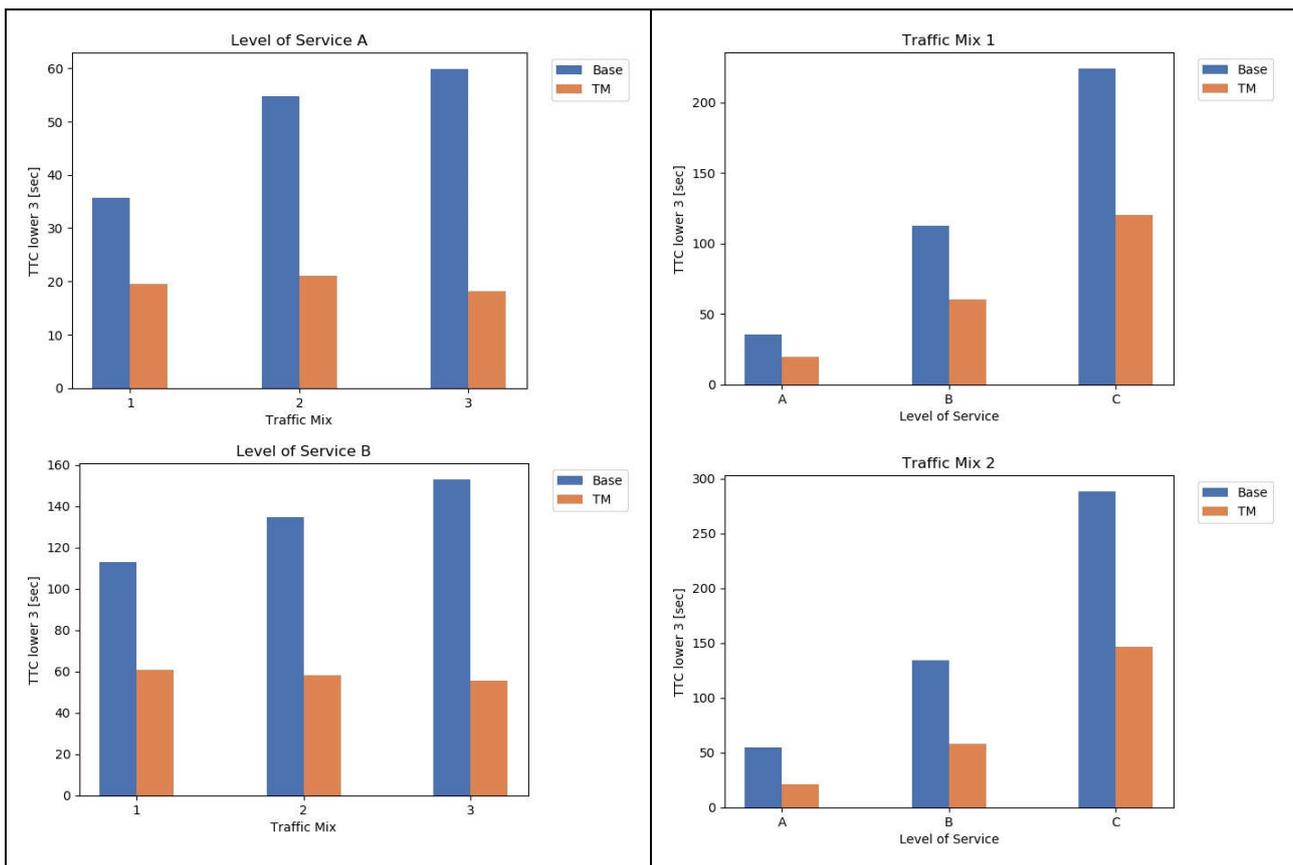


Figure 5: Example time-space diagrams for measured speeds and flows at LOS C with vehicle mix 2 for use case 1.1. The left group corresponds to the baseline simulations, the right group to those where Service 1 is applied.

2.1.3.2 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.



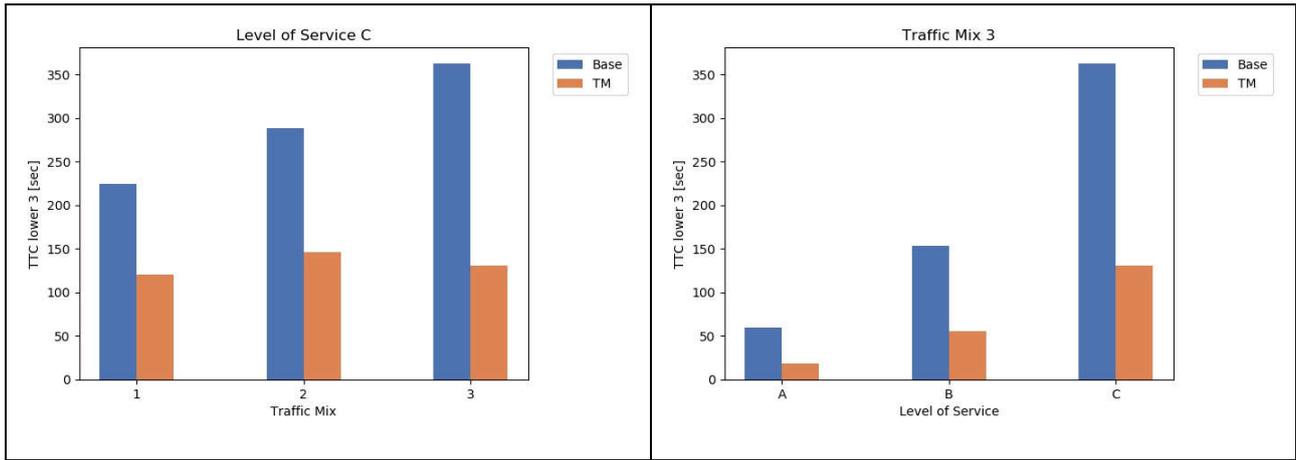
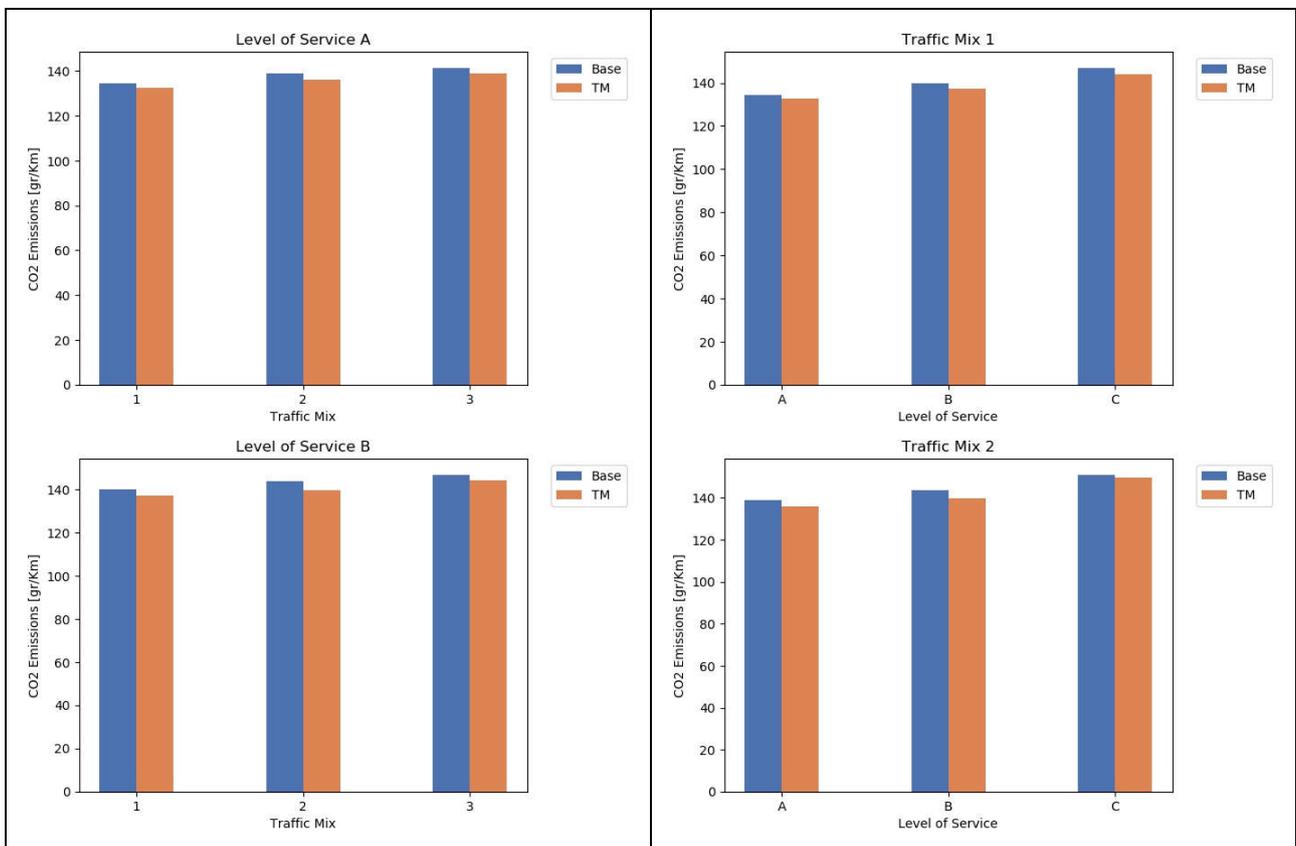


Figure 6: Average number of events with TTC below three seconds for use case 1.1 (varying the LOS and vehicle mix). Different bar colours correspond to the baseline and traffic management simulations.

2.1.3.3 Environmental impacts

For assessing the environmental impact of Service 1, we analyse the calculated emissions of CO₂. Figure 7 shows the average CO₂ 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 CO₂ emissions is not equal for every chart).

The results indicate that there is no significant difference in the overall CO₂ emission either with or without Service 1. The use of Service 1 results in a slight CO₂ reduction for LOS A and B and when C(A)V are not heavily deployed.



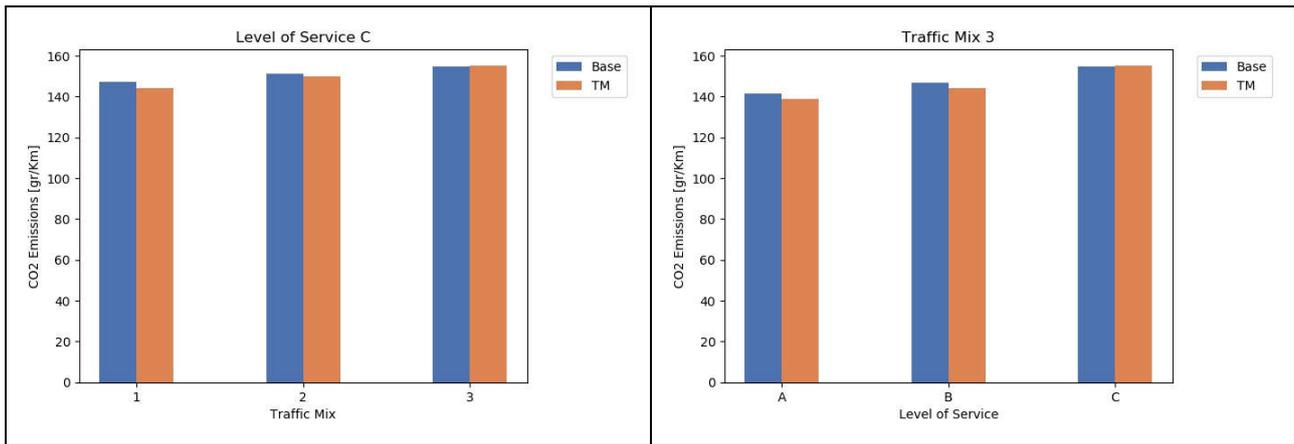


Figure 7: Average CO₂ emissions per kilometre travelled for use case 1.1 (varying the LOS and vehicle mixes). Different bar colours correspond to the baseline and traffic management simulations.

2.1.4 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 CO₂ 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)V 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)V 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.

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

2.2.1 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.

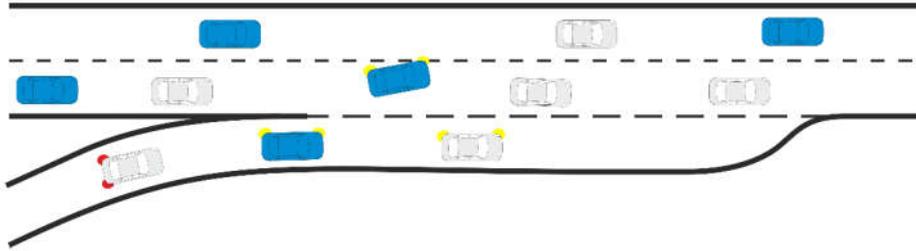


Figure 8: Schematic illustration of use case 2.1.

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:

$$r(k) = r(k - 1) + K_R [\hat{o} - o_{out(k)}] \quad (1)$$

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.

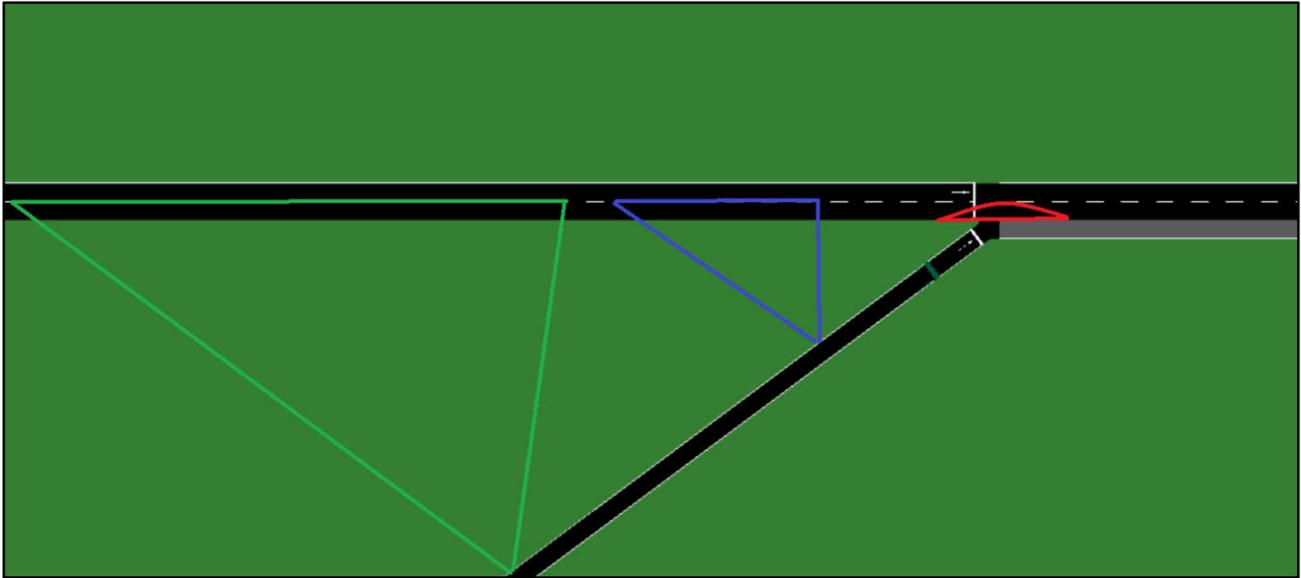


Figure 9: Schematic overview of the decision area for gap selection for AVs (red), LVs (blue), and infrastructure-assisted C(A)V (green).

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.

2.2.2 Traffic management setup

2.2.2.1 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).

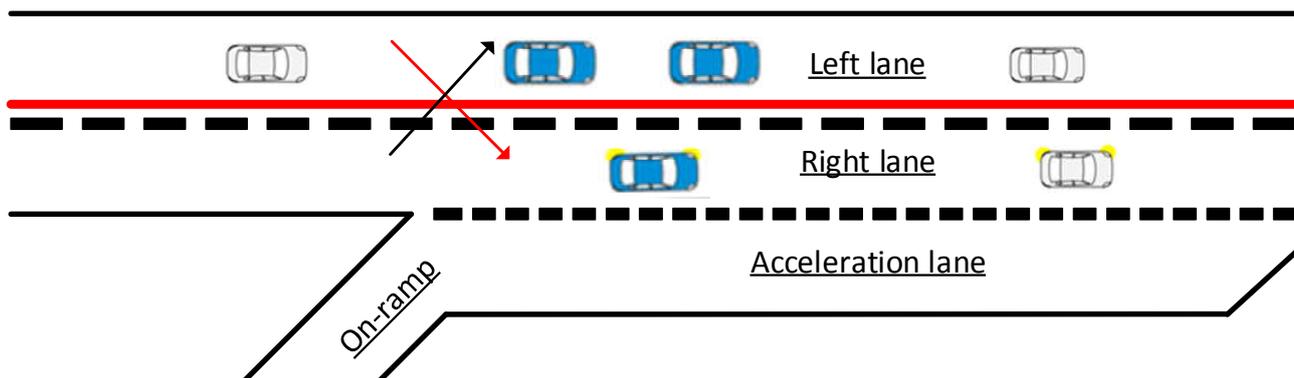


Figure 10: Schematics of the new lane advice strategy in current iteration.

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.

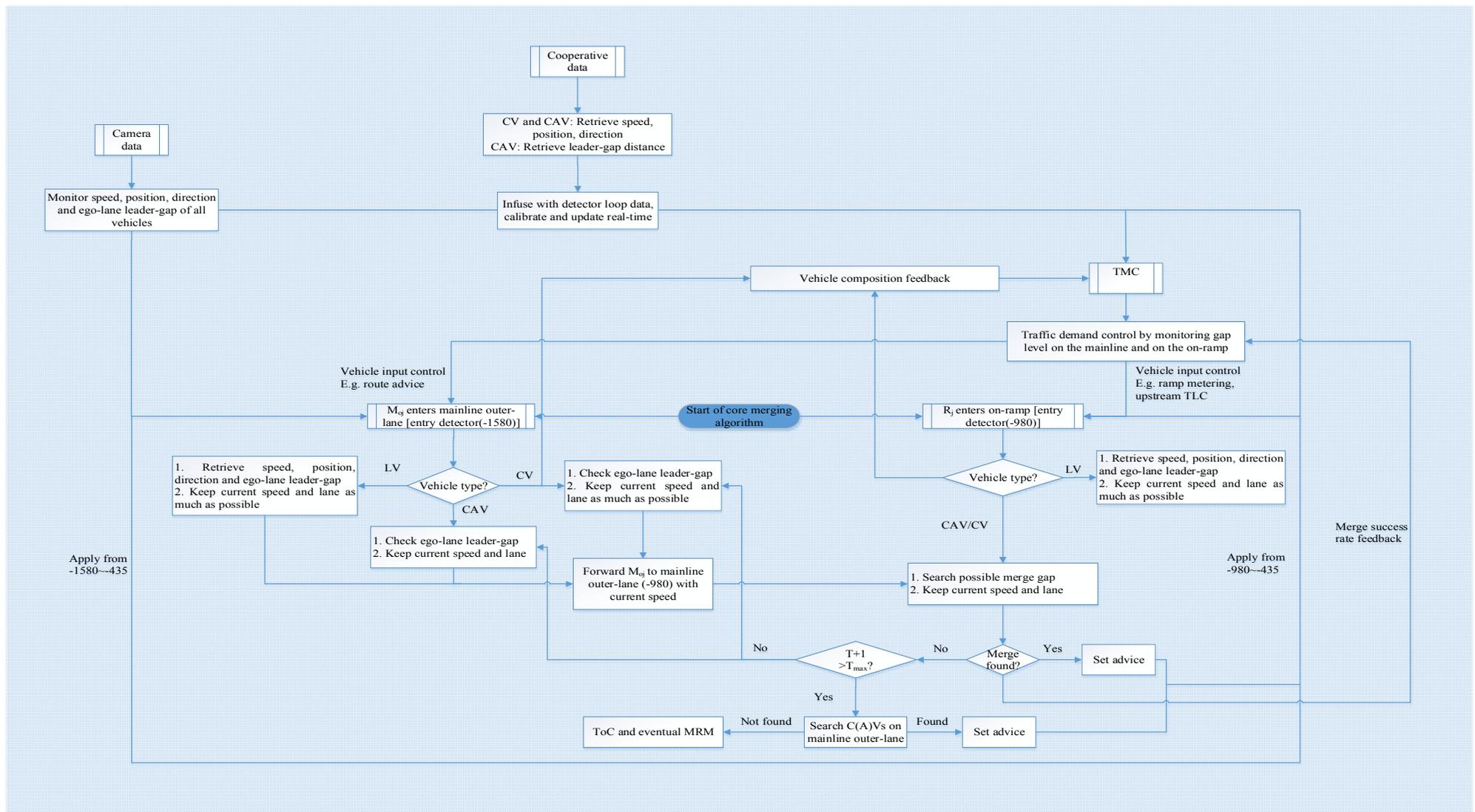


Figure 11: The core merging algorithm flow chart for Service 2.

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.

2.2.2.2 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.

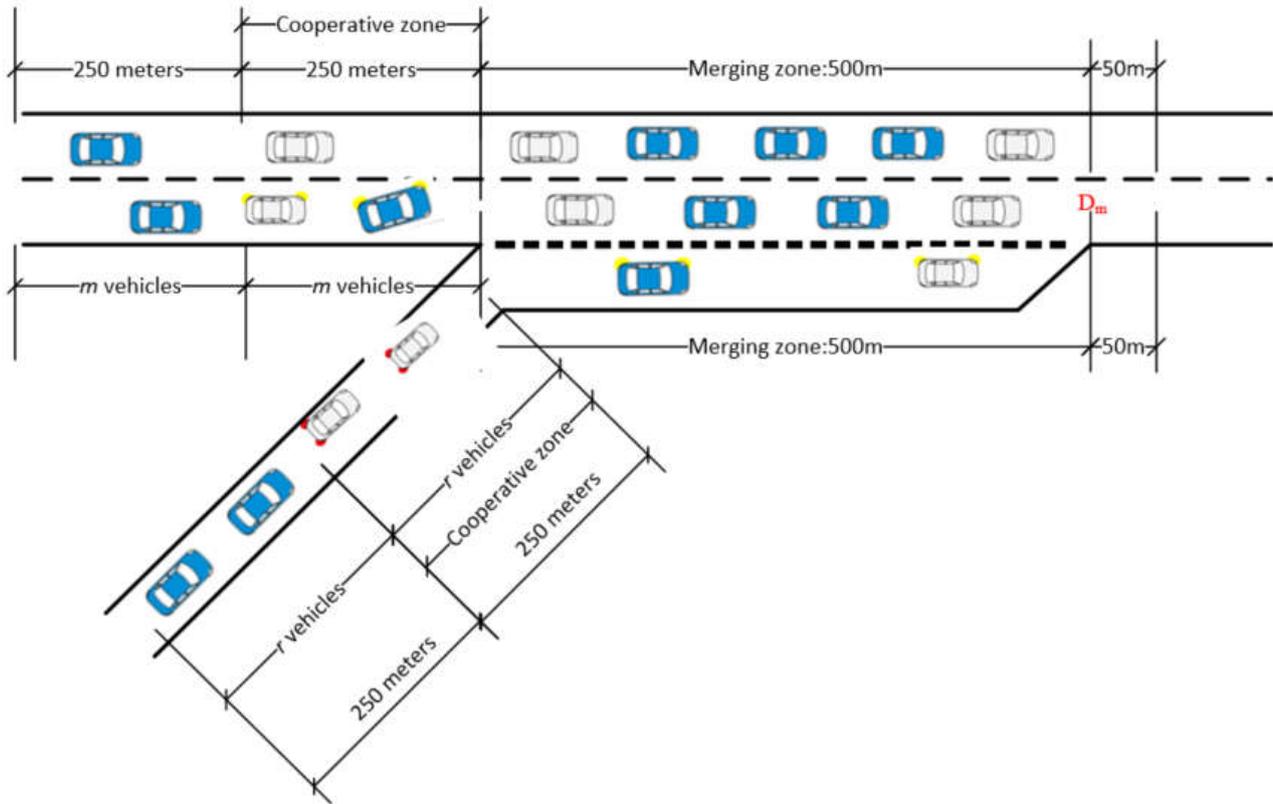


Figure 12: Merging zone schematic (baseline) of the network for use case 2.1.

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:

$\frac{d_M - MDP}{v_{\max}} \geq \frac{d_r - MDP}{v_{\min}}$	(1)
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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)

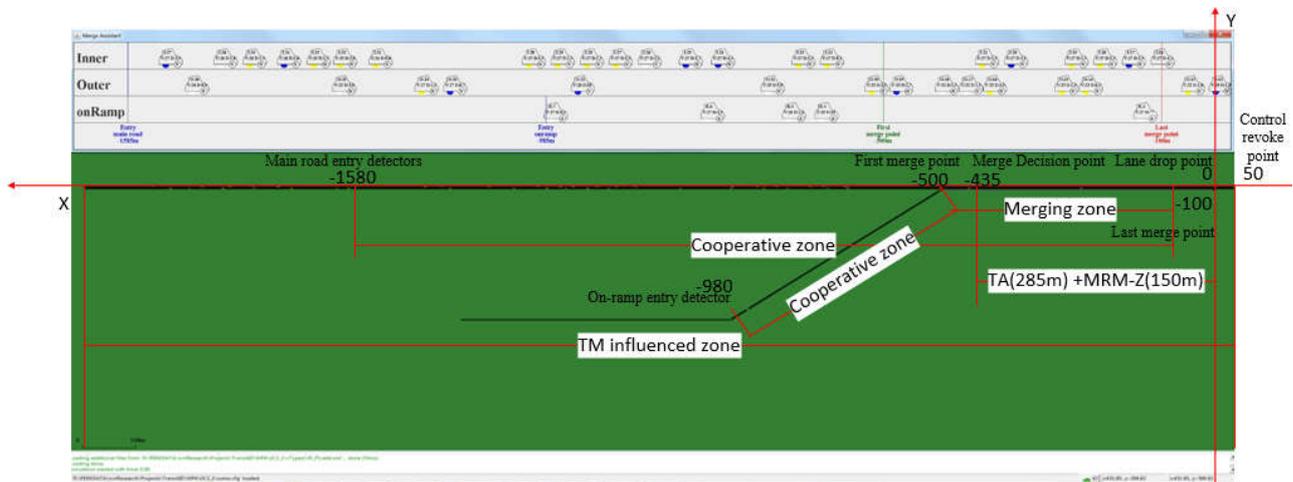


Figure 13: Zoning indication of the SUMO network for use case 2.1.

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) \times 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:

$$d = \frac{u^2}{2a_{\text{MRM}}} \quad (2)$$

where u is the vehicle initial speed, and a_{MRM} is the deceleration rate during MRM. For CAVs travelling with the speed limit $v_{\text{lim}} = 36.11$ m/s, and capable of braking during MRM with deceleration rate equal to $a_{\text{MRM}} = 3.0$ m/s², the braking distance is estimated equal to $d = 220$ m. The initial vehicle speed is 27.78 m/s, and a_{MRM} is the deceleration rate during MRM, which equals to 3.0 m/s². 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.

2.2.2.3 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	<ul style="list-style-type: none"> Highway: 1.5 km \rightarrow 2.5 km On-ramp: 0.5 km \rightarrow 1.0 km Acceleration lane: 0.5 km 	
Road priority	3	
Allowed road speed	<ul style="list-style-type: none"> Highway: 27.78 m/s On-ramp: 22.22 m/s \rightarrow 27.78 m/s 	<ul style="list-style-type: none"> Highway: 100 km/h On-ramp: 100 km/h
Number of nodes	7	<ul style="list-style-type: none"> jun1 - jun7 priority nodes
Number of edges	6	
Number of O-D relations (routes)	2	<ul style="list-style-type: none"> from jun1 to jun7 from jun3 to jun7
Number of lanes	1-2-3-2	<ul style="list-style-type: none"> 1 lane on-ramp 2 normal lanes on highway 3 lanes at merging zone (from jun4 to jun5, including acceleration lane)

		<ul style="list-style-type: none"> • 2 lanes downstream of the merging zone. Thus, a lane drop from 3 to 2 lanes at the end of merging zone.
Filenames	<ul style="list-style-type: none"> • network: UC2_1.net.xml 	
Merging area length	0.5 km	
Network layout		
Network layout		
Road segments		
<p>jun1→ jun2: Insertion and speed stabilization area (100 m→1100 m, 2 lanes)</p> <p>jun2→ jun4: mainline motorway (500 m, 2 lanes)</p> <p>jun3→ jun4: on-ramp (500 m→1000 m, 1 lane)</p> <p>jun4→ jun5: mainline motorway with acceleration lane (500 m, 3 lanes)</p> <p>jun5→ jun6: mainline motorway (300 m, 2 lanes)</p> <p>jun6→ jun7: exit (100 m, 2 lanes)</p>		

2.2.2.4 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.

2.2.3 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.

2.2.3.1 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	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).

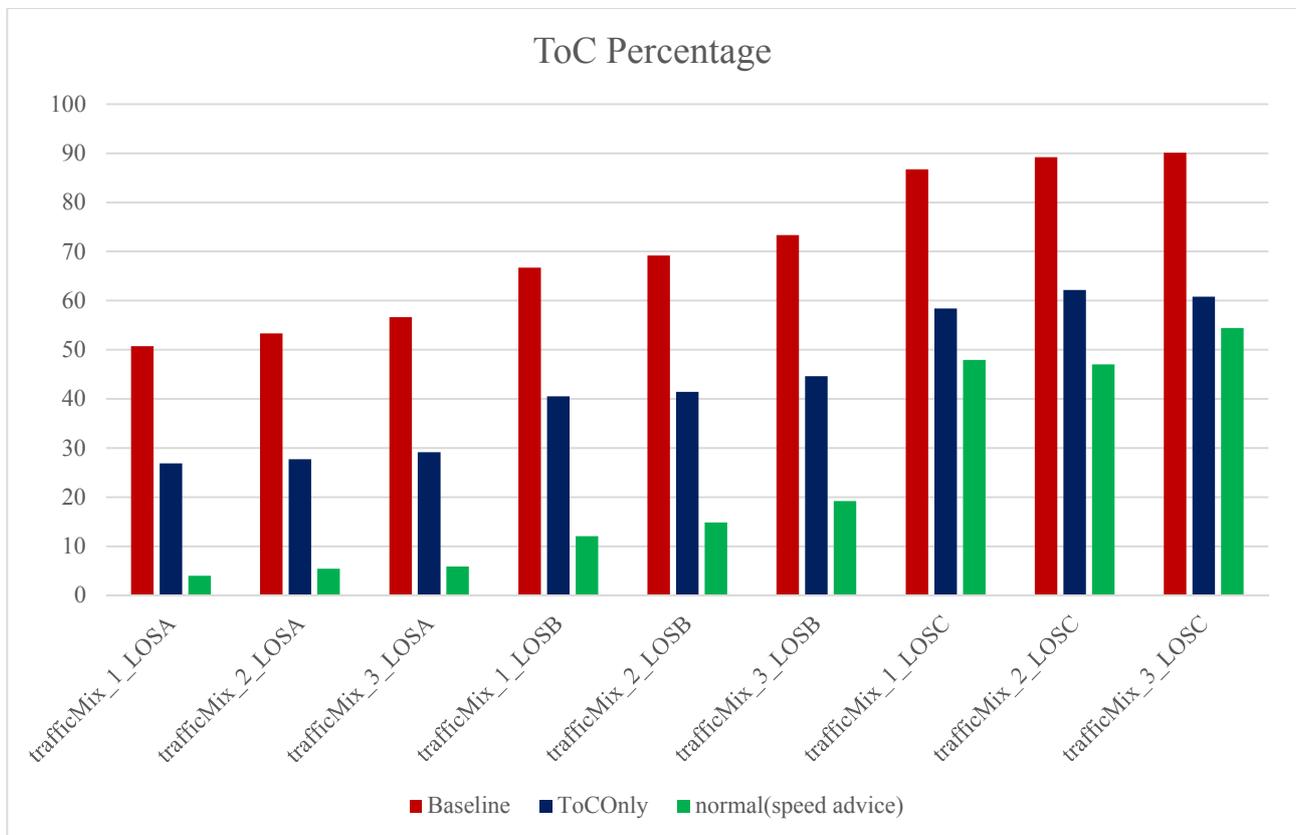


Figure 14: ToC% of baseline, ToCOnly and normal, under vehicle mix 1, 2, and 3, and LOS A, B, and C.

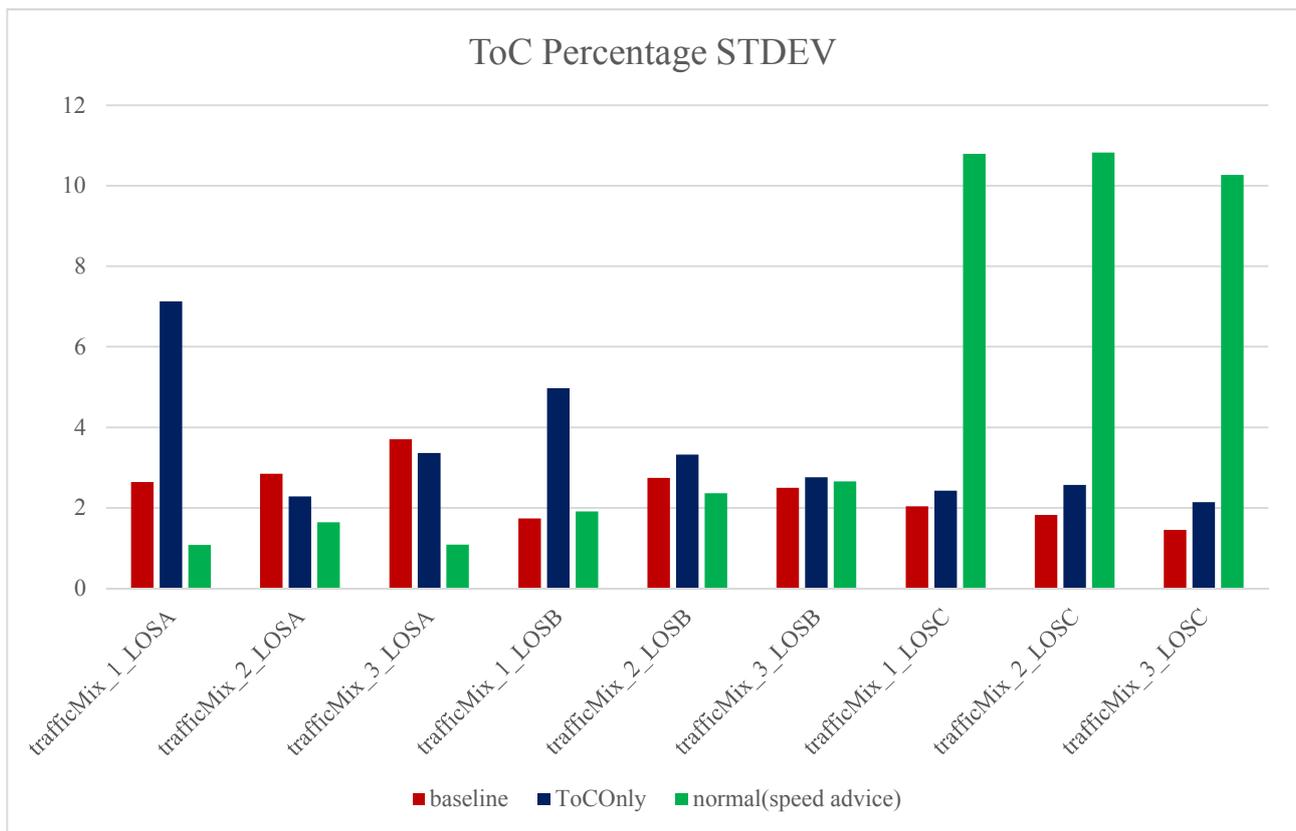


Figure 15: ToC% Standard Deviation of baseline, ToCOnly and normal, under vehicle mixes 1, 2, and 3, and LOS A, B, and C.

2.2.3.2 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.

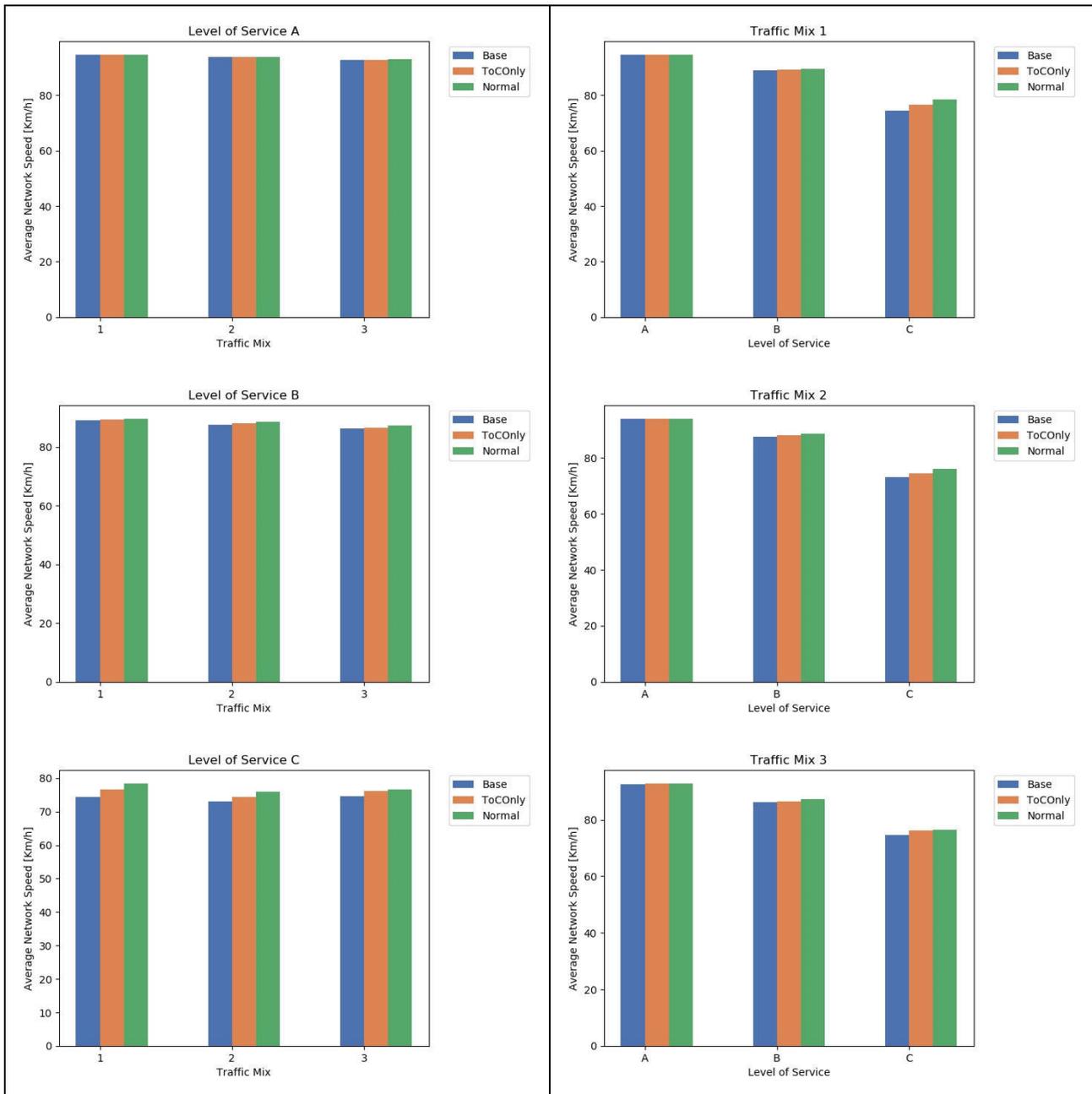


Figure 16: Average network speed for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

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.

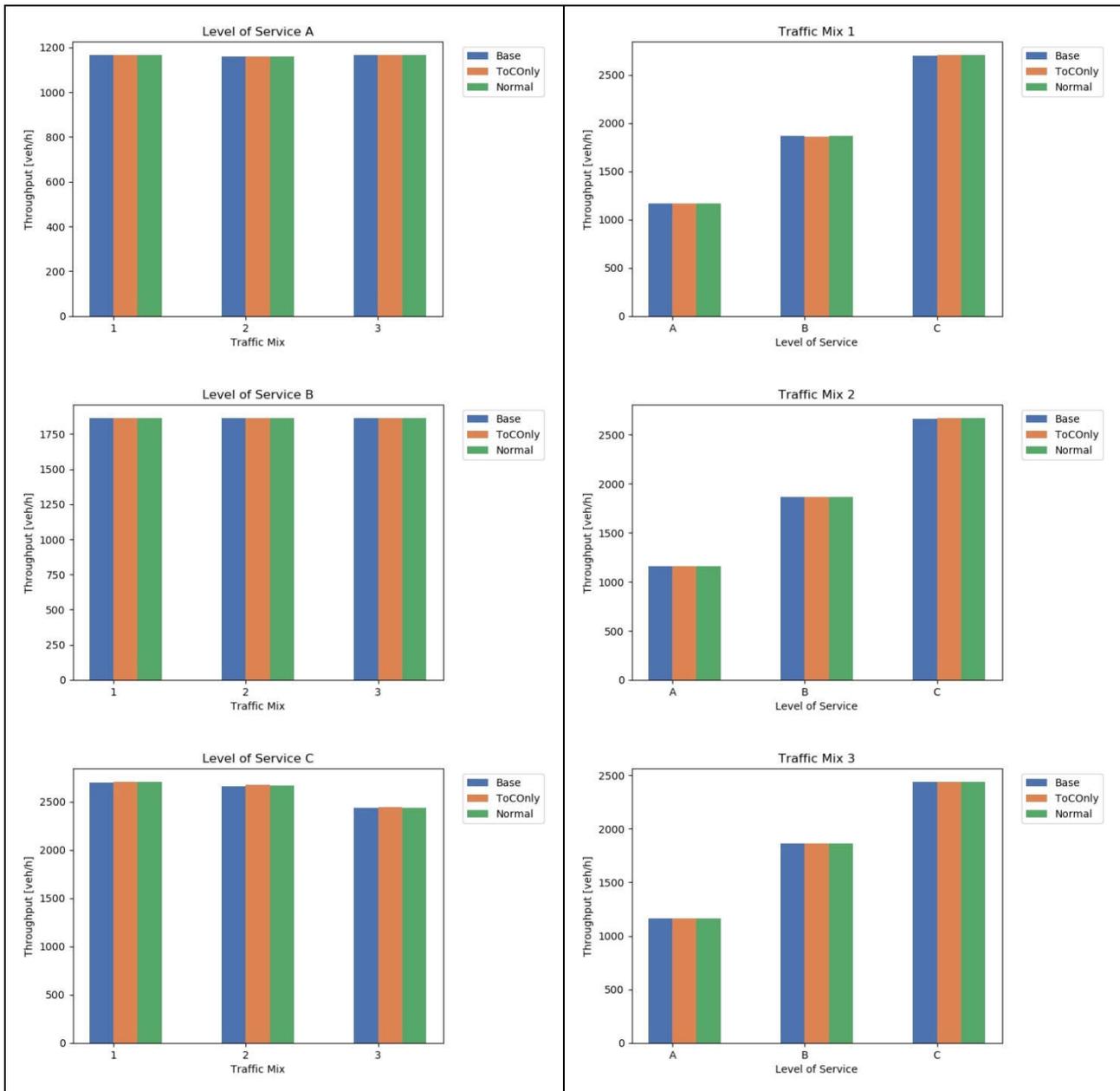


Figure 17: Throughput for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

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).

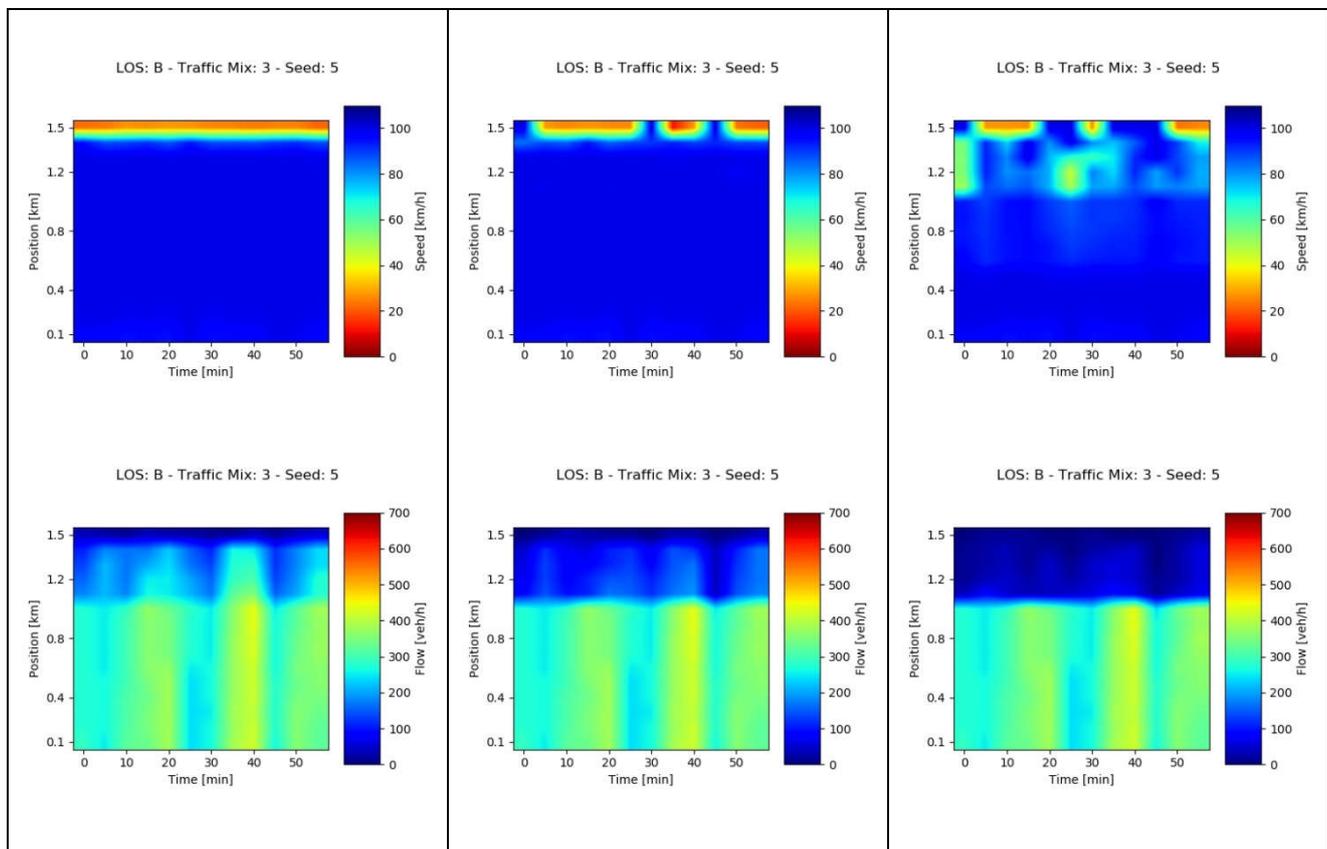


Figure 18: Example time-space-diagrams (on-ramp) of measured speeds (upper row) and flows (bottom row) for baseline (left column), ToCOnly (middle column), and speed advice (right column), for use case 2.1 (LOS B, vehicle mix 3, seed 5).

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.

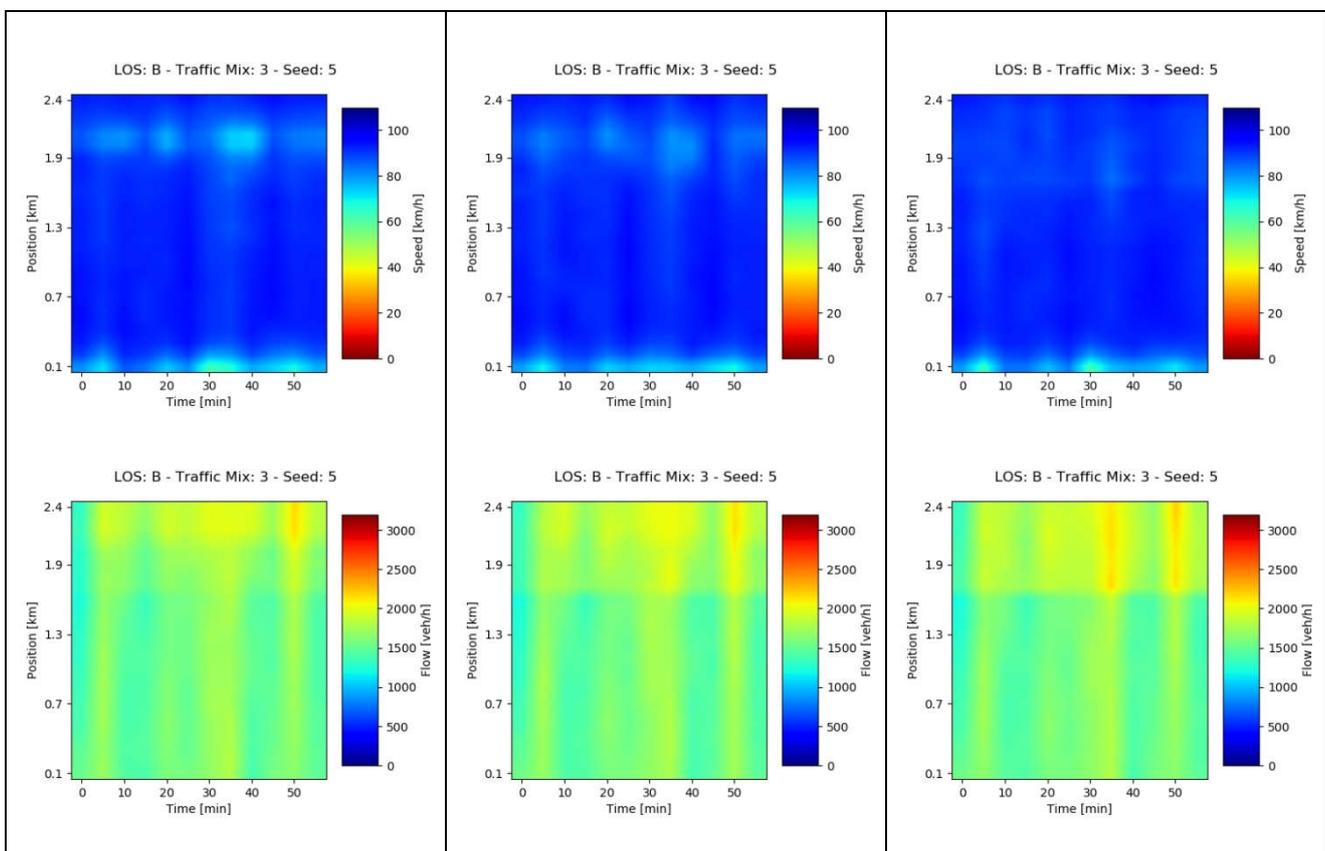


Figure 19: Example time-space-diagrams (mainline) of measured speeds (upper row) and flows (bottom row) for baseline (left column), ToCOnly (middle column), and speed advice (right column), for use case 2.1 (LOS B, vehicle mix 3, seed 5).

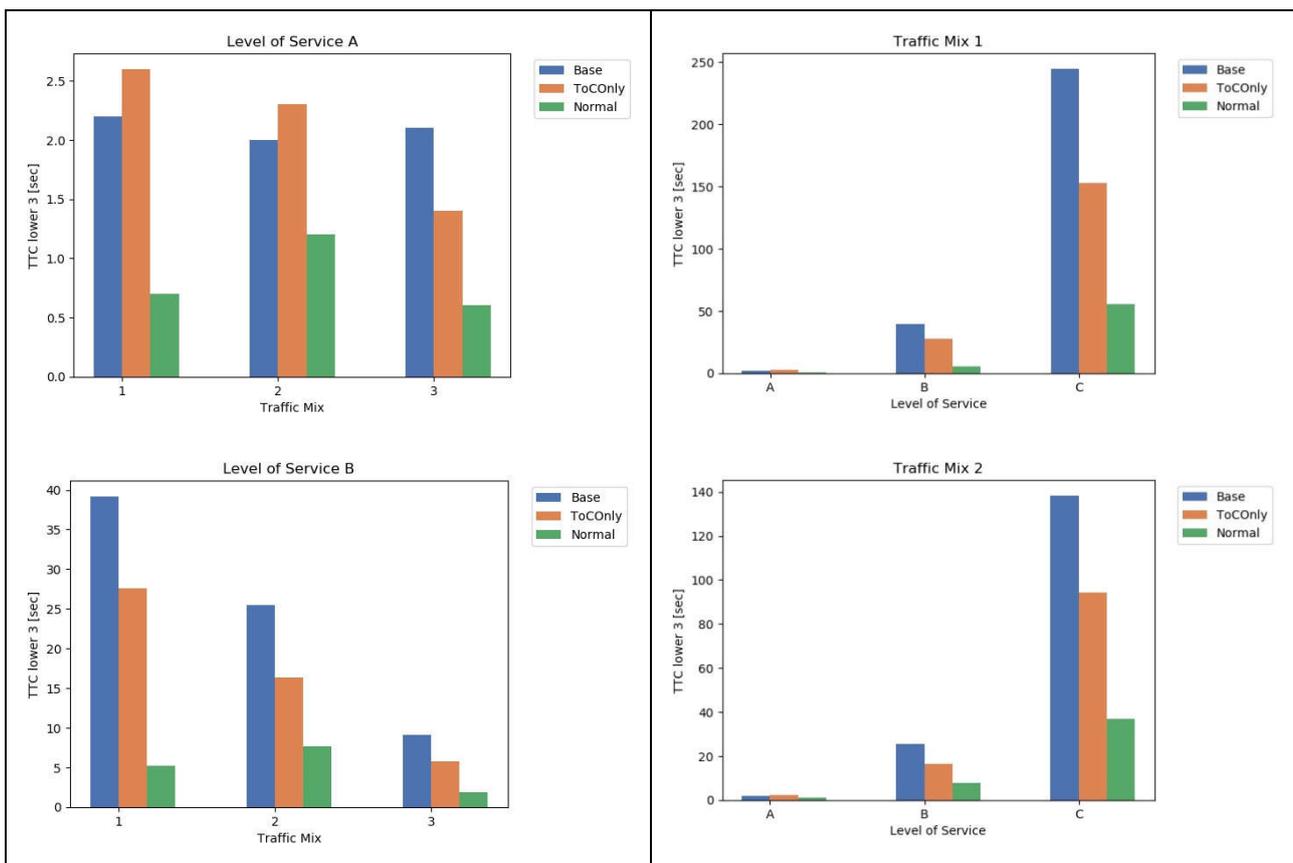
2.2.3.3 Impacts on traffic safety

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.



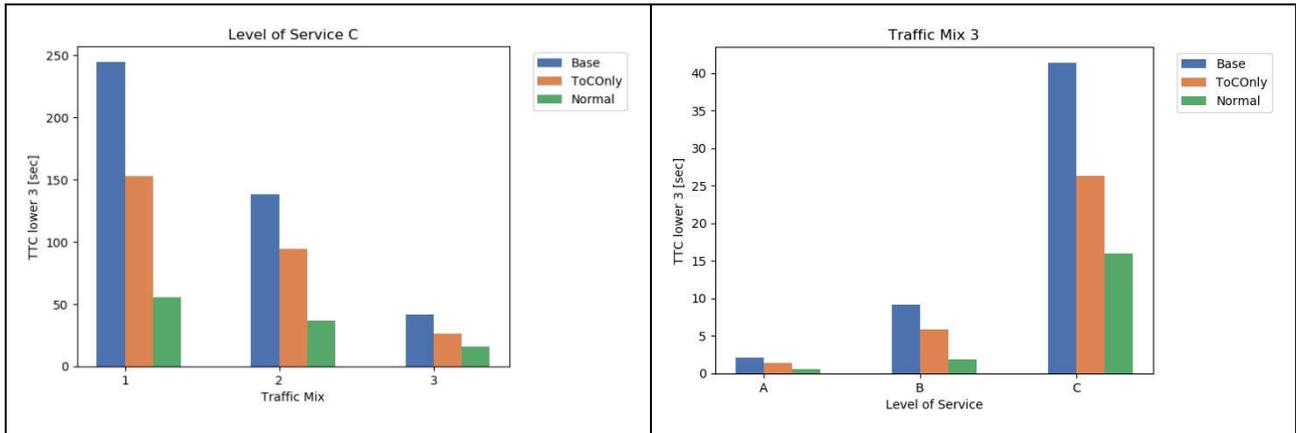
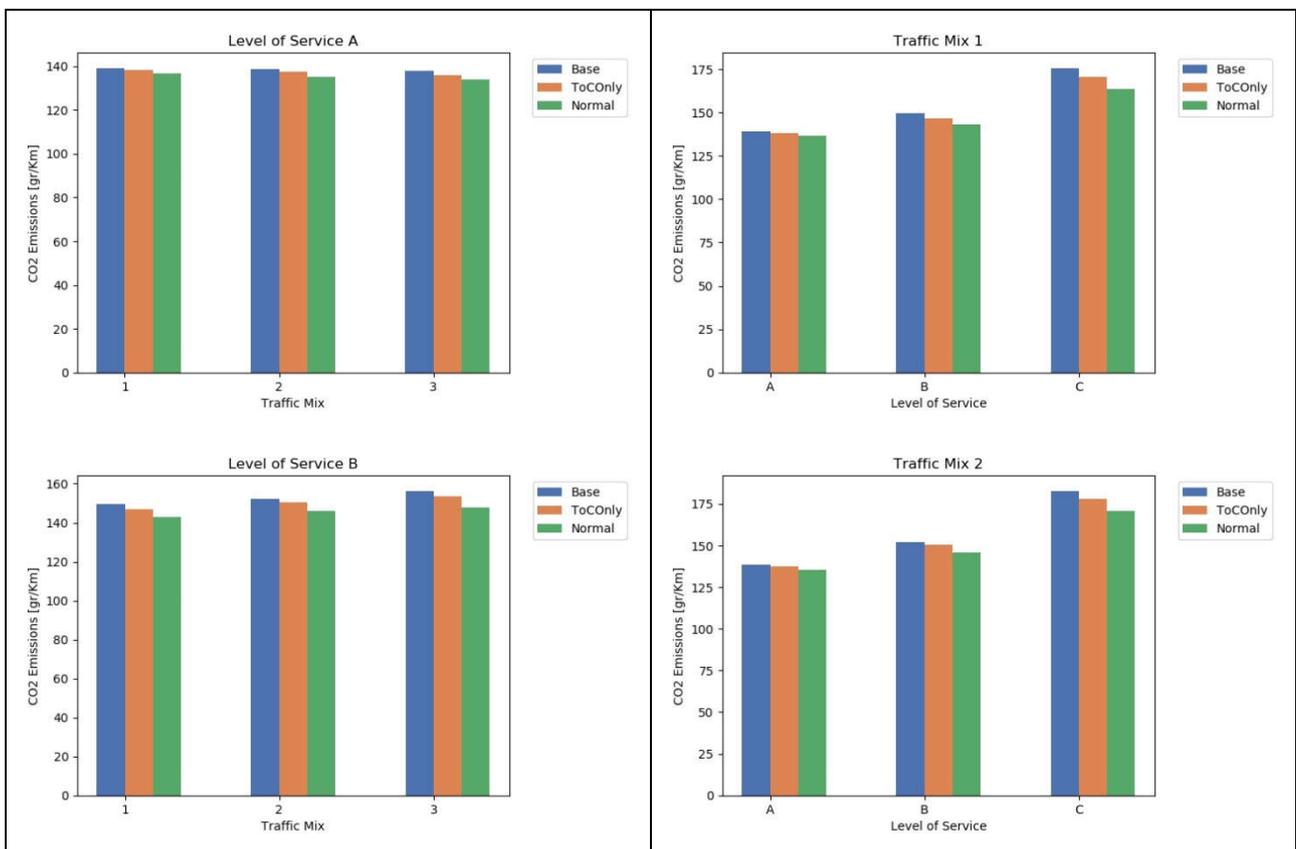


Figure 20: TTC lower than 3 s for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

2.2.3.4 Environmental impacts

Figure 21 shows the average CO₂ 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 CO₂ emissions may vary for each plot.

For each scenario, baseline, ToCOnly, or normal, the average CO₂ emissions increase together with the traffic demands and vehicle mixes. A reduction of average CO₂ 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).



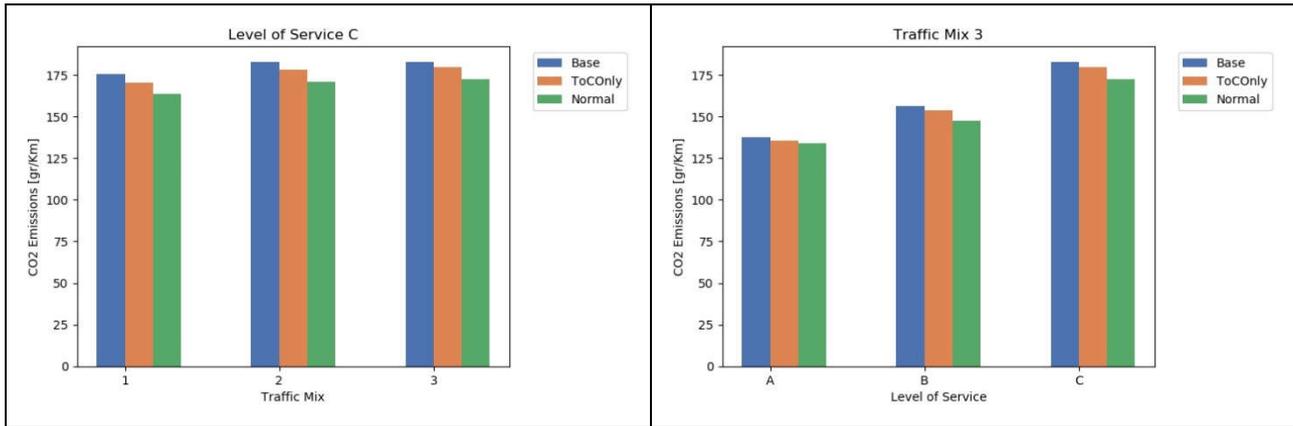


Figure 21: CO₂ emissions for use case 2.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline, ToCOnly, and speed advice.

2.2.4 Discussion

2.2.4.1 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 \times 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.

2.2.4.2 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.

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

2.3.1 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).

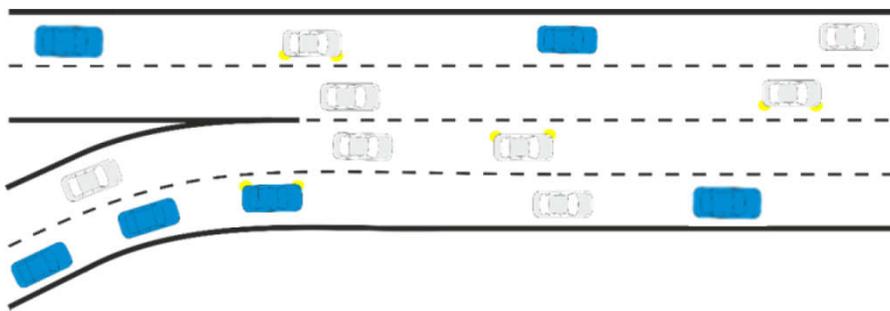


Figure 22: Schematic illustration of use case 3.1.

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.

2.3.2 Traffic management setup

2.3.2.1 Description of the areas

2.3.2.1.1 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.

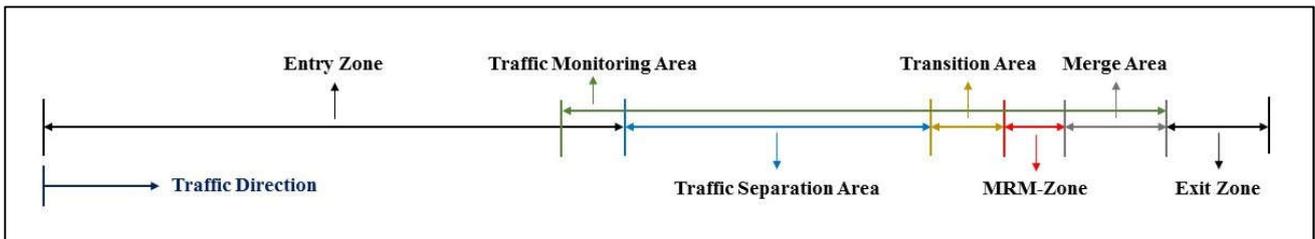


Figure 23: Schematic illustration of the Traffic Management Area (TMA).

2.3.2.1.2 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.

2.3.2.1.3 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 $\bar{t}_{lc} = 4.5$ s. However, there is currently no relevant information published regarding CAVs/CVs. Considering that the speed limit is set equal to $v_{lim} = 36.11$ 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 $\bar{s}_{lc} = 125$ 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 $f_{LOS(C)} = 1500$ pcu/h/lane according to the Highway Capacity Manual of the National Research Council (2010). The latter traffic flow rate corresponds to $f_{LOS(C)} = 50$ 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 $s_{TSA} = 1500$ m to the TSA.

2.3.2.1.4 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 $t_{MRM} = 10$ s, and the speed limit is $v_{lim} = 36.11$ m/s, the TA should stretch approximately $s_{TA} = 360$ m.

2.3.2.1.5 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 $s_{MRM-Z} = 300$ m.

2.3.2.1.6 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 $s_{MA} = 500$ m downstream of the MA.

2.3.2.2 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 $s_{upstream} = 500$ m. However, this length cannot accommodate the needs of the TSP, since it was previously determined that the TMA should span at least $s_{TMA} = s_{TMNA} + s_{TSA} + s_{TA} + s_{MRM-Z} + s_{MA} = 2960$ 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 $s_{upstream} = 5000$ 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		
<p>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</p>		

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)

2.3.2.3 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.

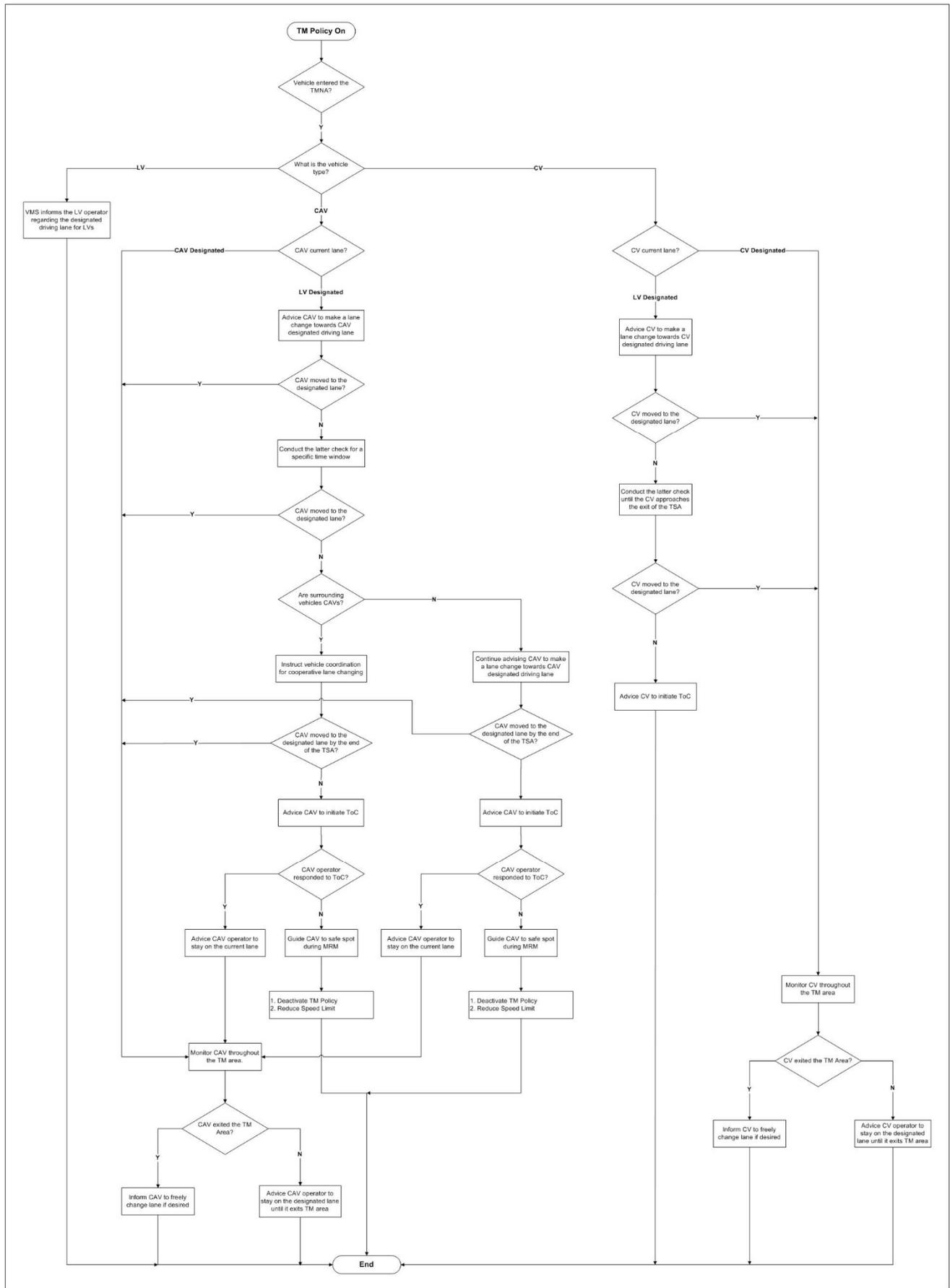


Figure 24: Traffic Separation Policy (TSP) control logic.

2.3.2.3.1 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).

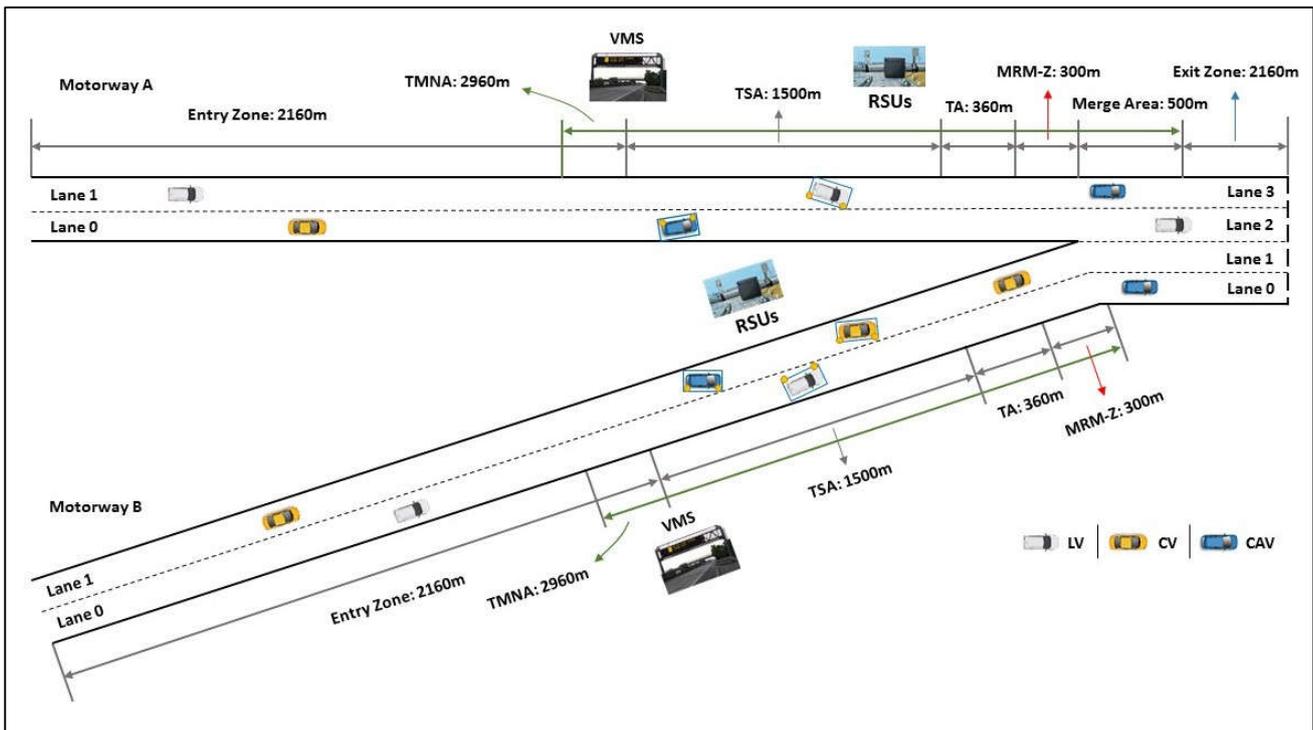


Figure 25: Successful implementation of Traffic Separation Policy.

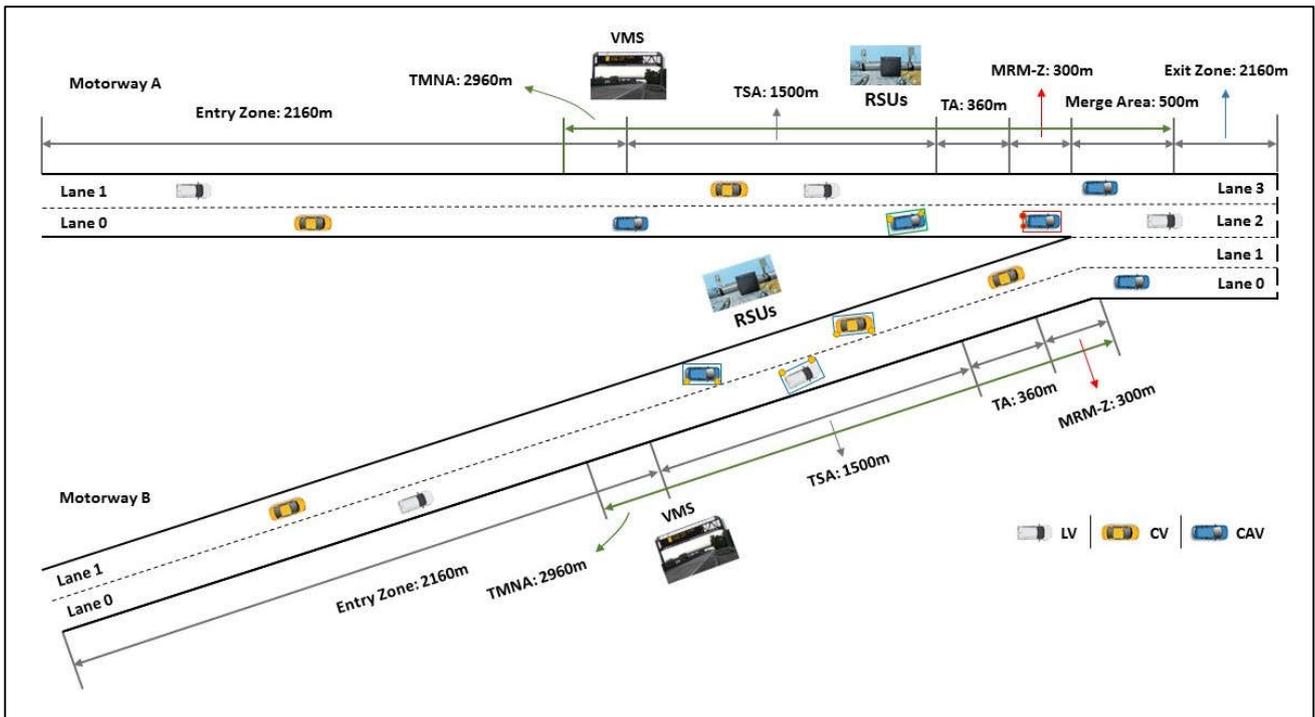


Figure 26: Traffic Separation Policy disrupted by Minimum-Risk Manoeuvre (MRM).

2.3.2.3.2 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.

2.3.2.3.3 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.

2.3.3 Results

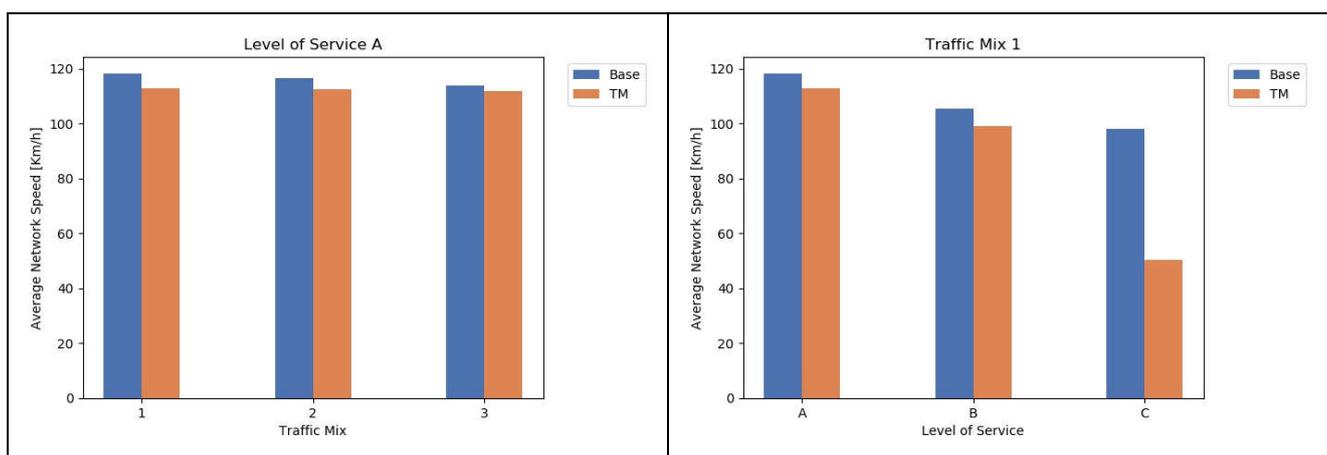
2.3.3.1 Impacts on traffic efficiency

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.



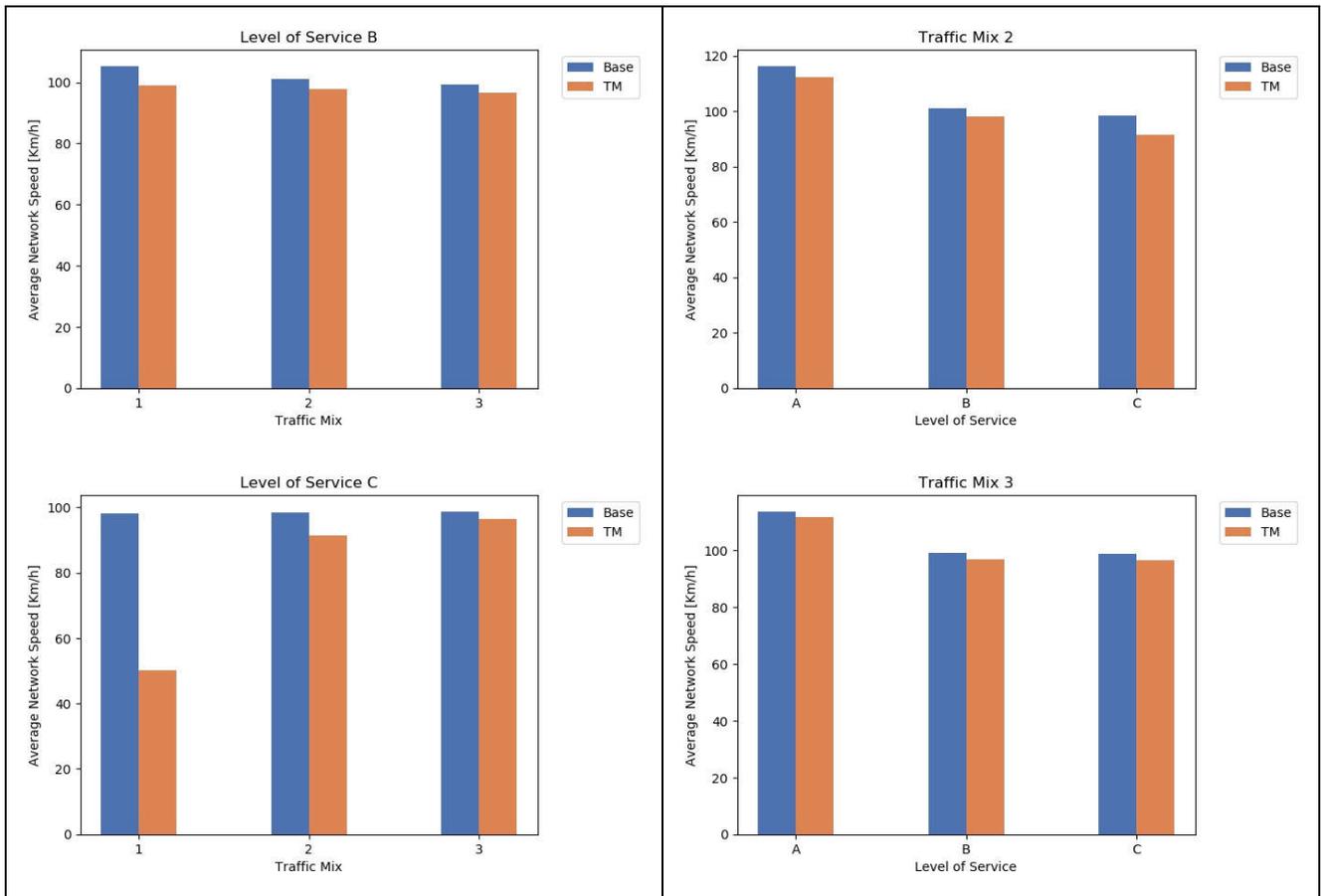


Figure 27: Average network speeds for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

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.

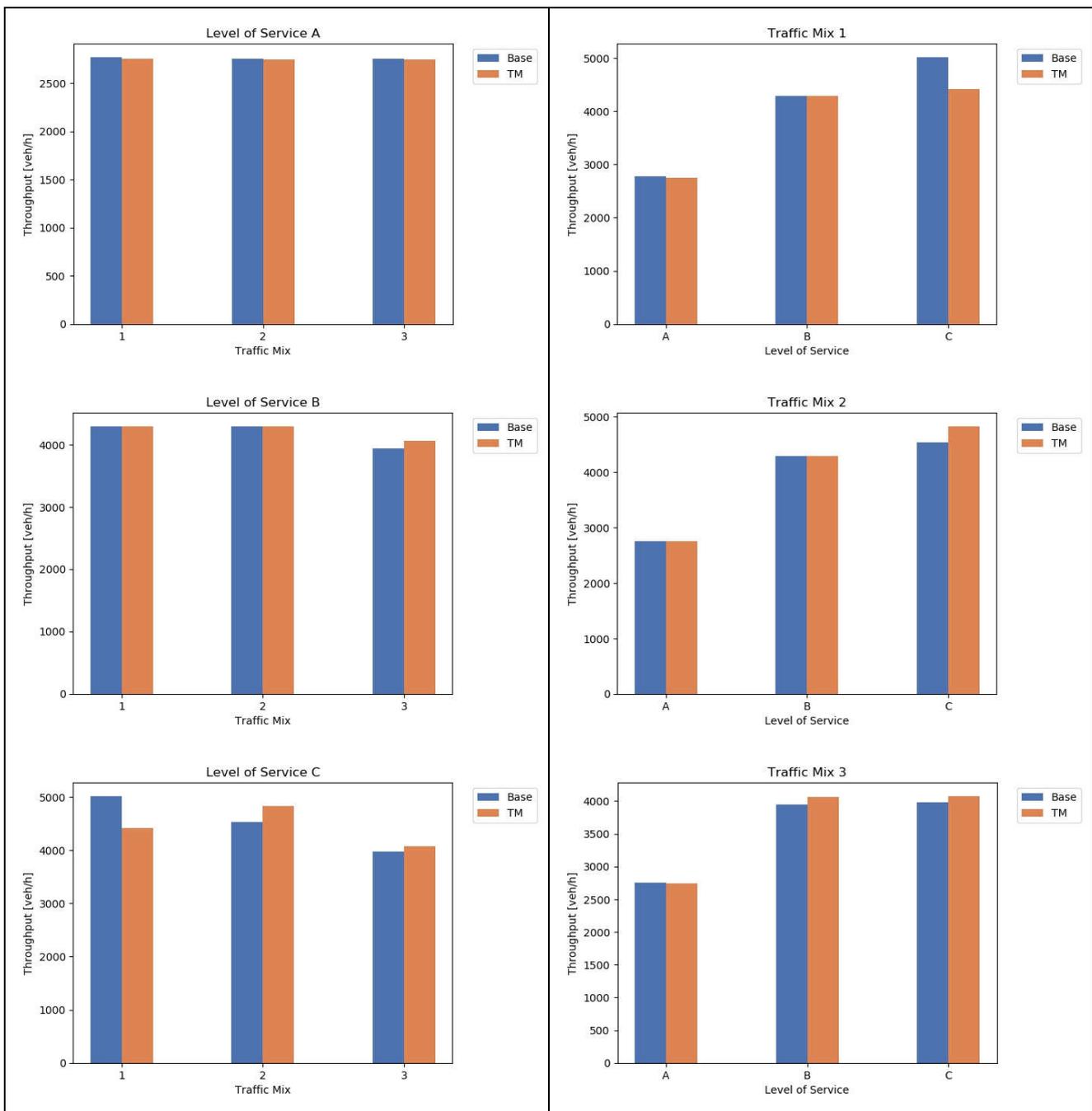


Figure 28: Throughput for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

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).

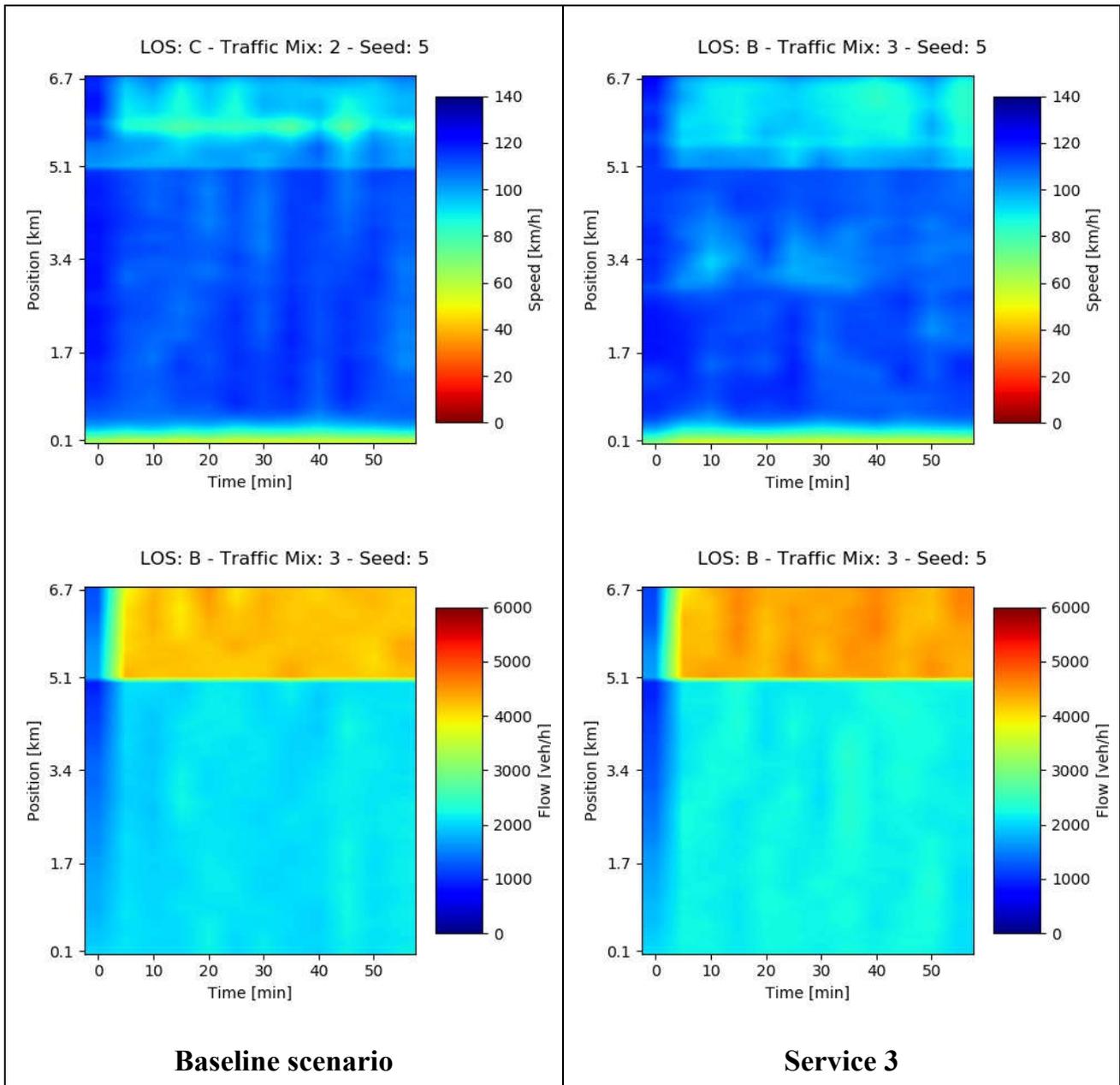


Figure 29: Example speed and flow tempo-spatial diagrams for use case 3.1 (LOS B, vehicle mix 3). The left column corresponds to the baseline scenario and the right column to the traffic management (Service 3) scenario.

2.3.3.2 Impacts on traffic safety

Traffic safety deteriorates for most of the examined scenarios (varying traffic demand levels and traffic 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 traffic mix, this phenomenon occurs for all traffic demand levels. However, when the share of C(A)V 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.

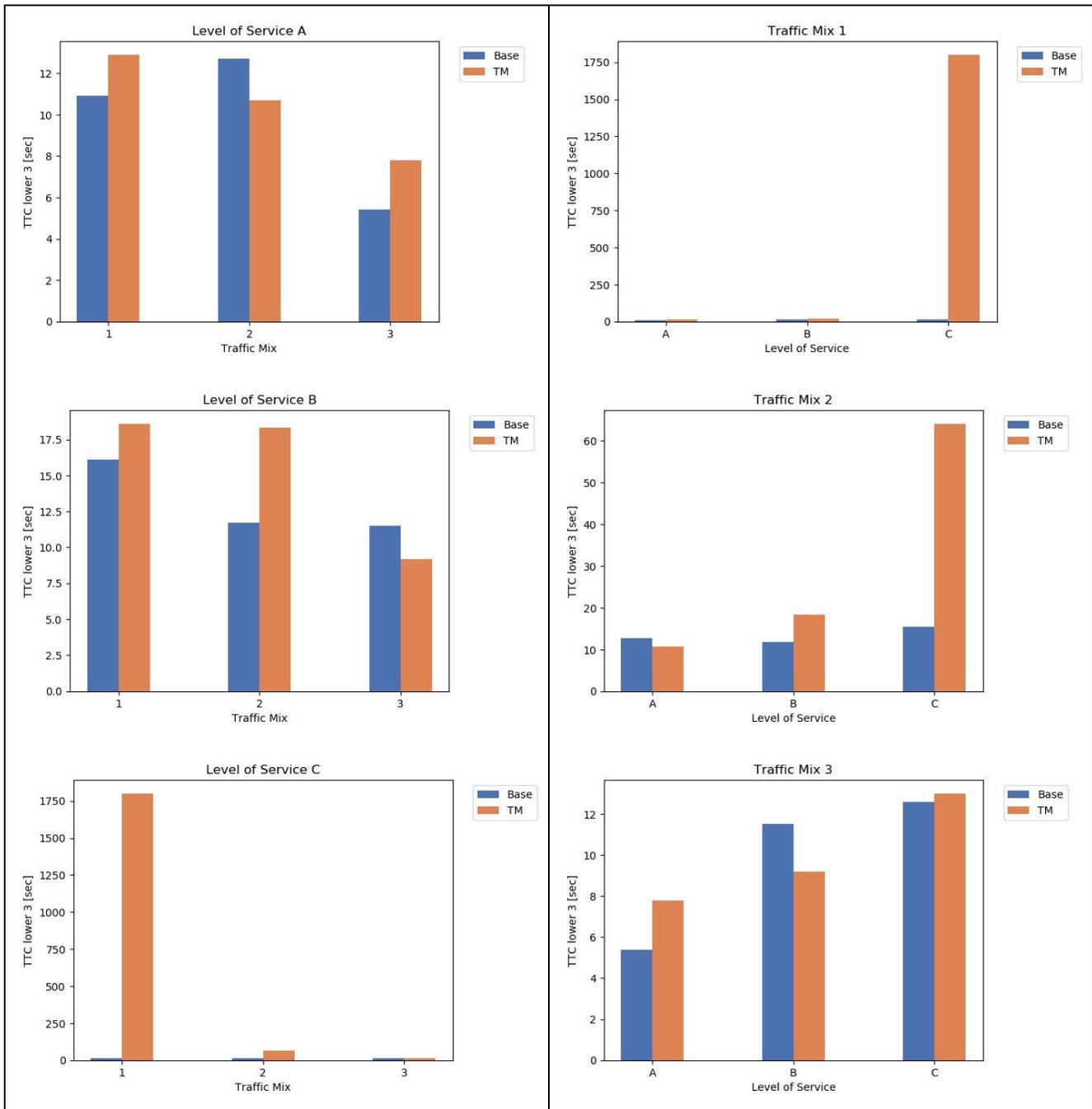


Figure 30: Average number of safety-critical events (TTC < 3.0 s) for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

2.3.3.3 Environmental impacts

CO₂ emissions differ marginally between the baseline and the traffic separation case, except for simulation scenarios corresponding to LOS 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, CO₂ emissions increase significantly when the share of LVs is high and traffic demand is medium (LOS C). On the other hand, CO₂ emissions are slightly higher for the baseline case when the rest of the simulation scenarios (traffic

demand levels and traffic mixes) are considered. These latter findings also comply with average network speed plots presented in Figure 29.

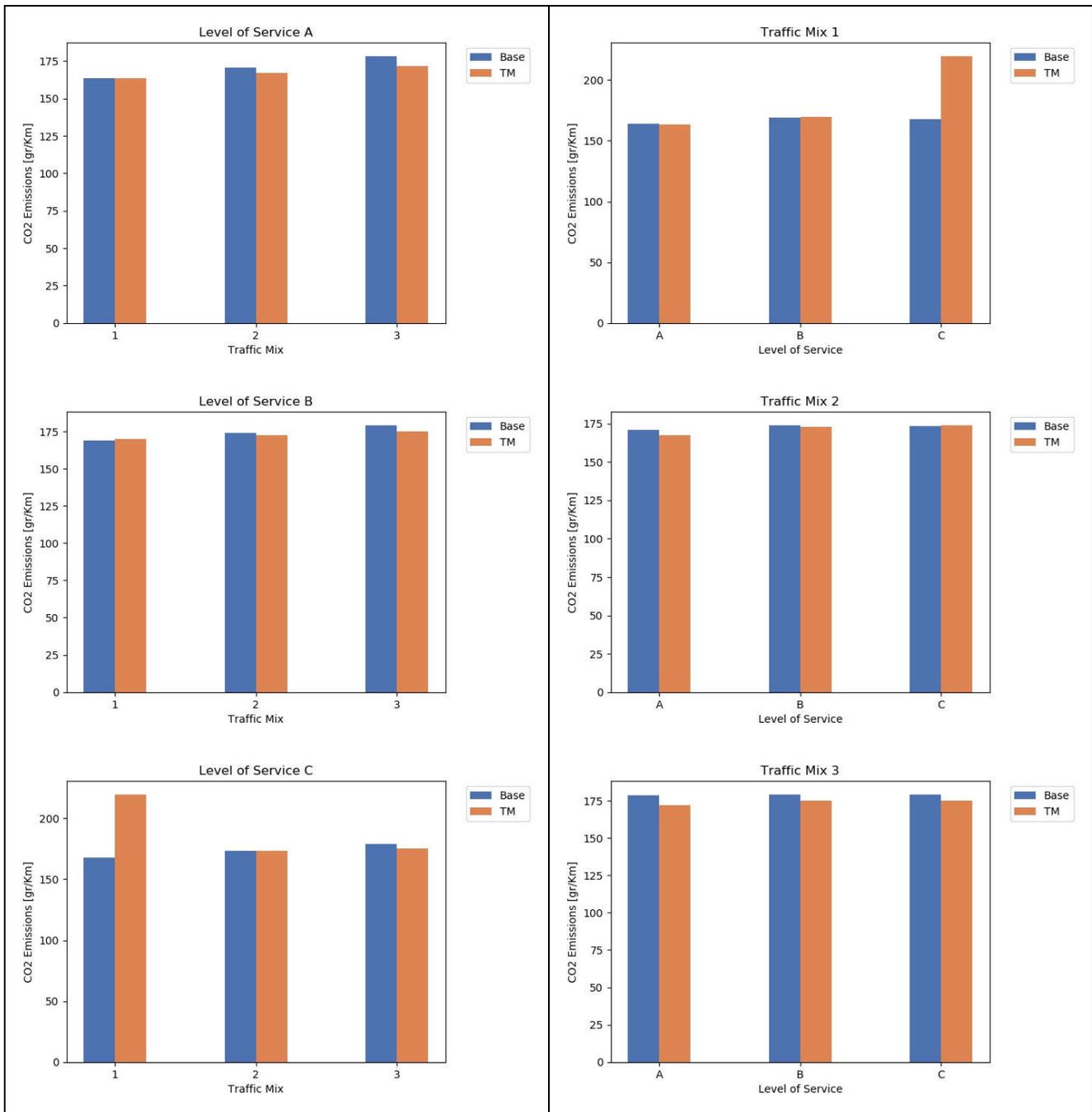


Figure 31: Average CO₂ emissions per kilometre travelled for use case 3.1 simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

2.3.4 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 traffic 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 from 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 CO₂ emissions differ slightly between the baseline and the traffic separation case.

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

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 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.

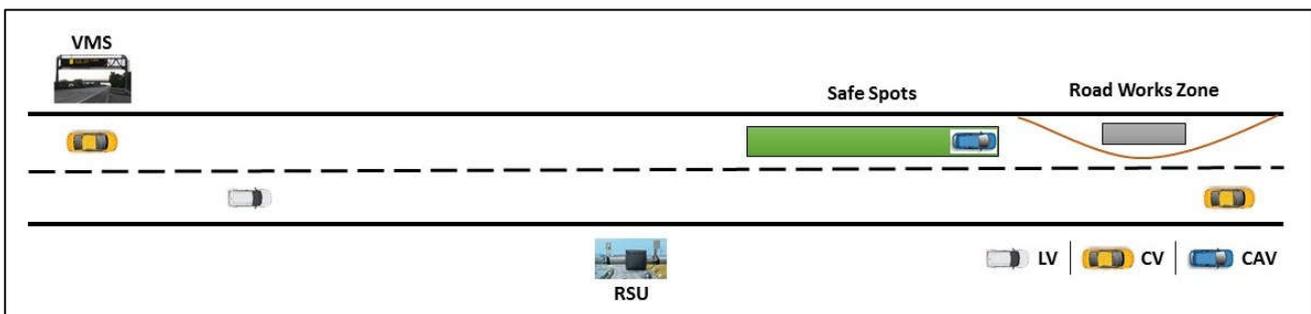


Figure 32: Safe spots upstream of road works zone.

2.4.2 Traffic management setup

2.4.2.1 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.

2.4.2.2 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.

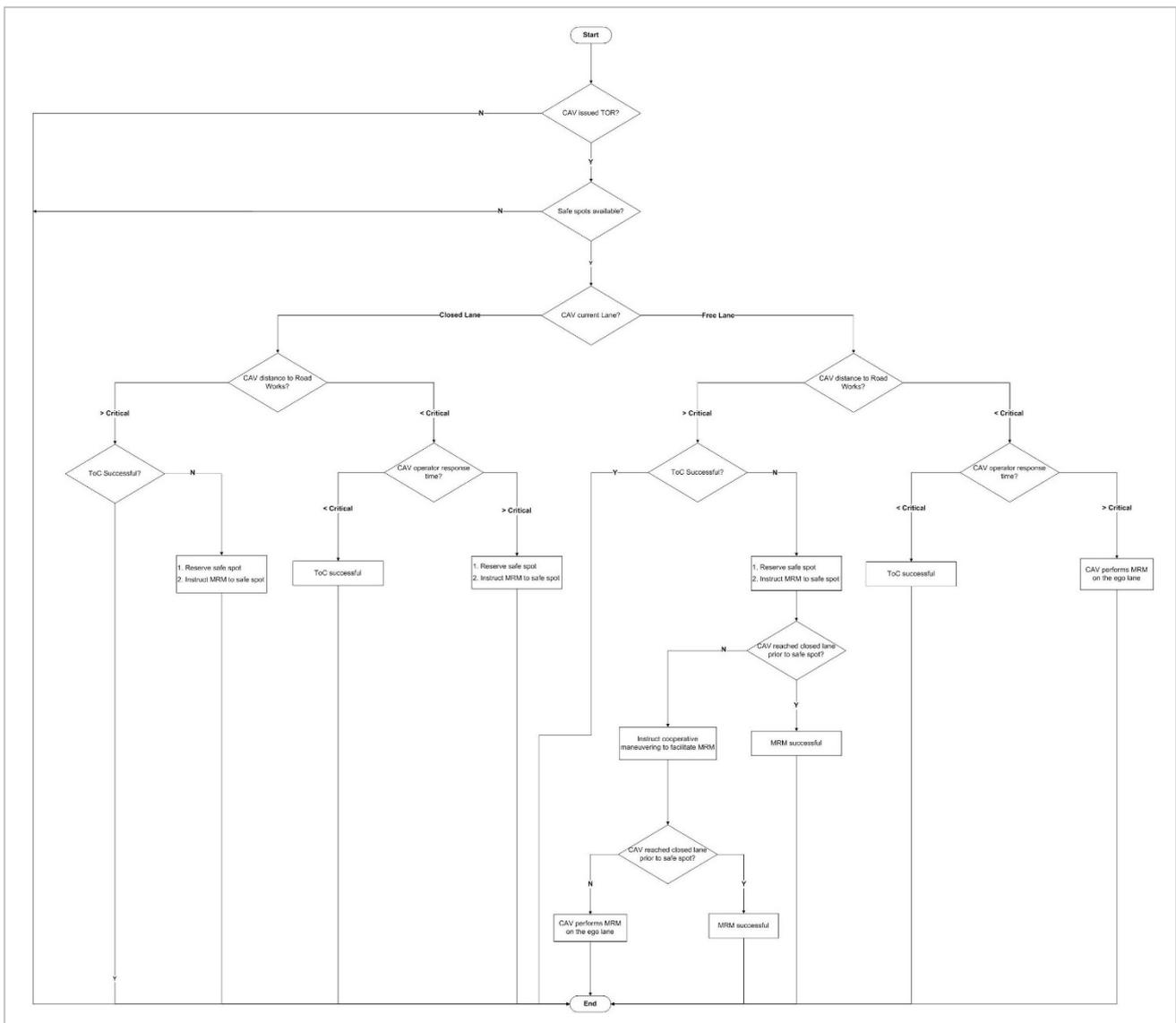


Figure 33: Control logic of the MRM management scheme.

2.4.2.3 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 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 $v_{lim}^{urb} = 13.89$ m/s for the urban case, and $v_{lim}^{mot} = 27.78$ m/s for the motorway case (upstream of the work zone). Since the time until the MRM was previously set $t_{MRM} = 10$ s, then the Transition Area (TA) should stretch approximately $s_{TA}^{urb} = 140$ m for the urban network, and $s_{TA}^{mot} = 280$ 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 ($a_{MRM} = 3.0$ m/s²). The MRM zone length is estimated using the equation elaborated in Section 2.2.2.2. Thus, in the urban network it spans approximately $s_{MRM-Z}^{urb} = 35$ m, and in the motorway network $s_{MRM-Z}^{mot} = 130$ m. Finally, the critical distance is determined to be $d_{crit}^{urb} = 200$ m for the urban scenario, and $d_{crit}^{mot} = 500$ m for the motorway scenario (see also Figure 34).

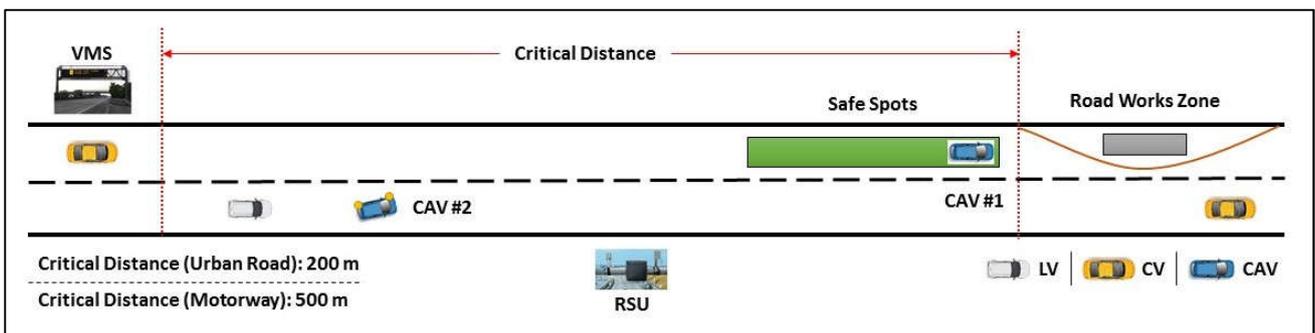


Figure 34: Critical distance upstream of the road works zone.

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.

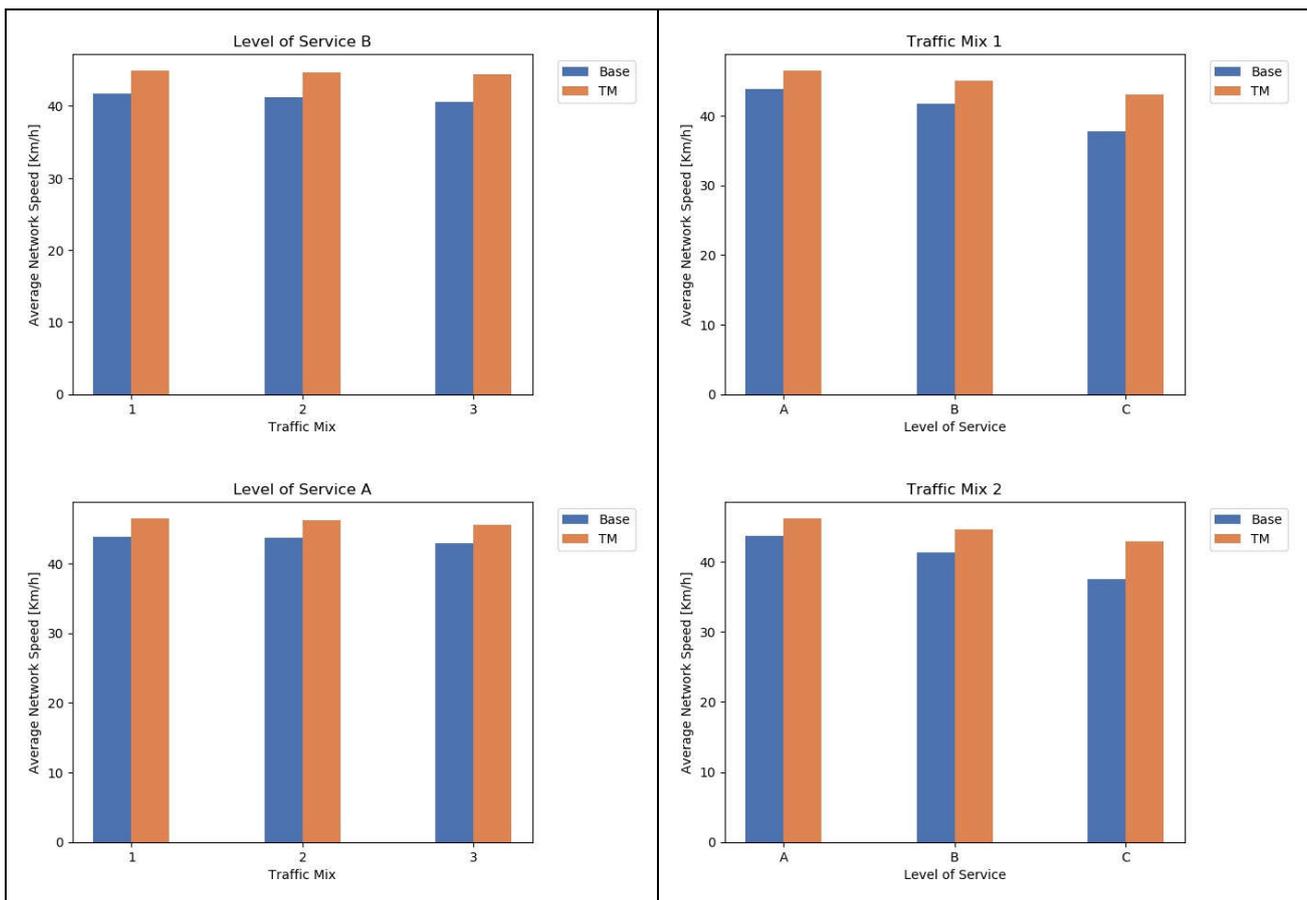
2.4.3 Results

2.4.3.1 Urban scenario

2.4.3.1.1 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.



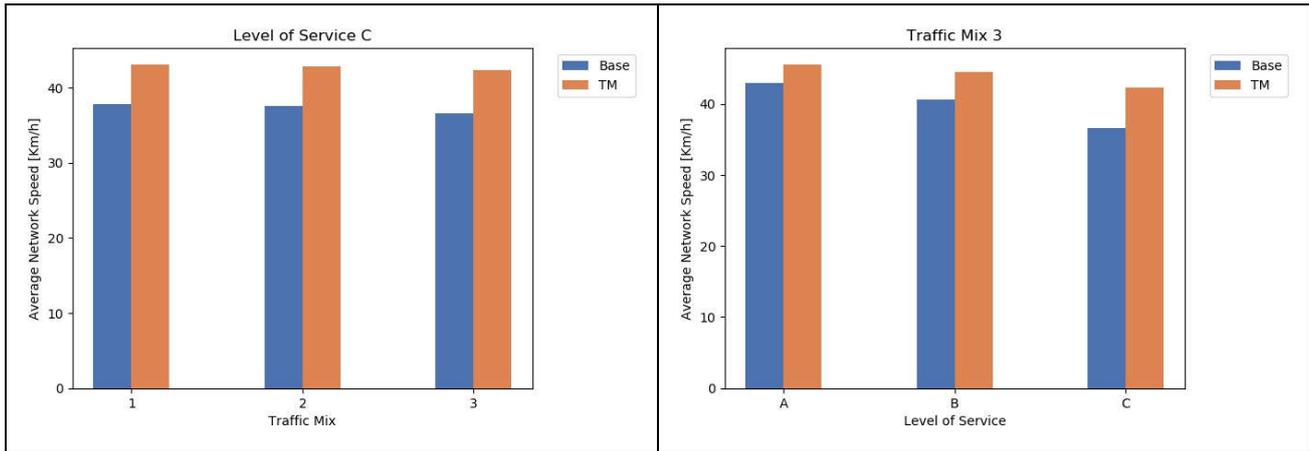
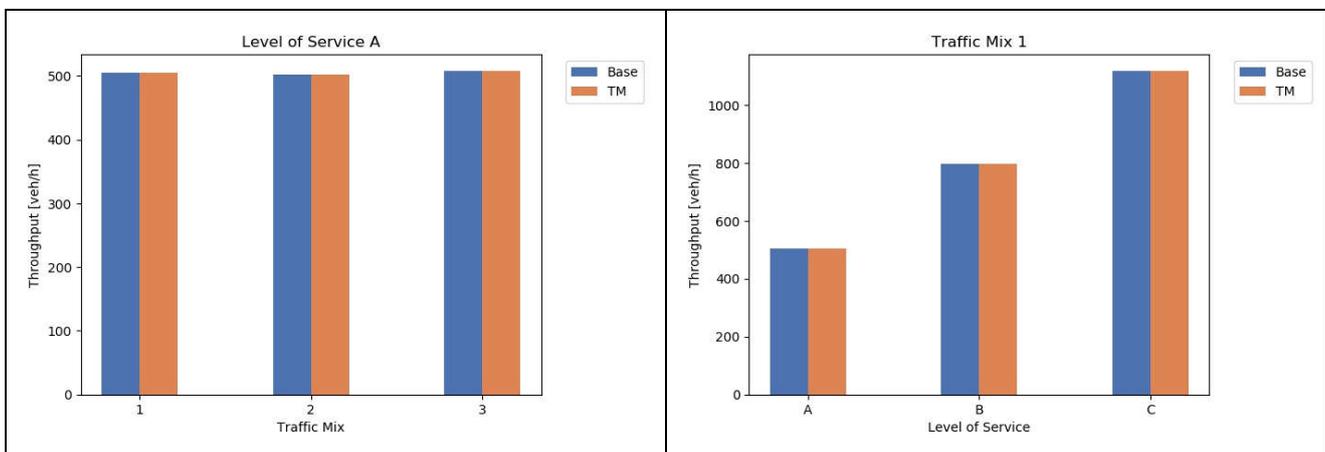


Figure 35: Average network speed for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

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.



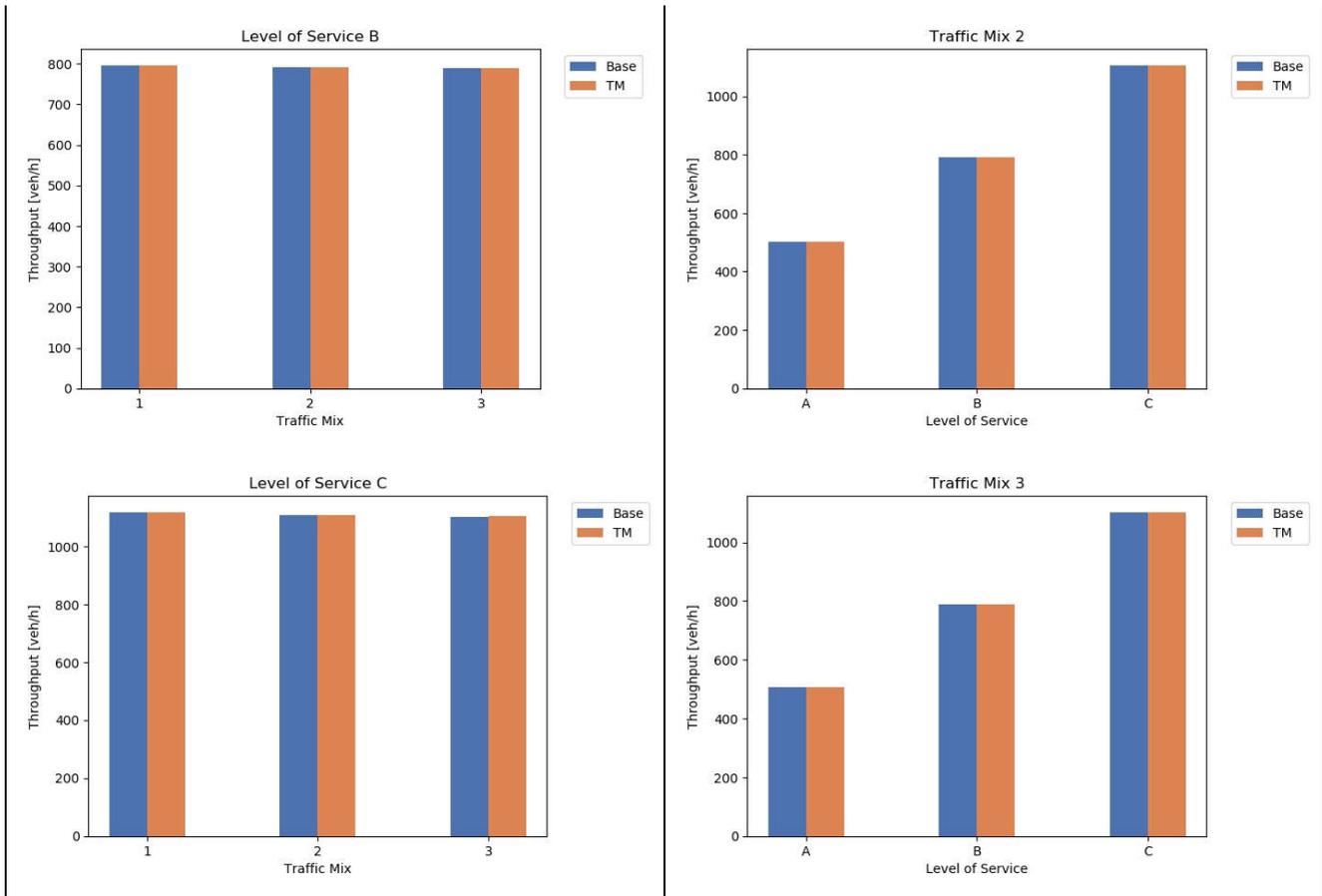


Figure 36: Throughput for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

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 $t_{\text{stop}} = 9$ min and location $x_{\text{stop}} = 0.9$ km, and thus congestion propagates upstream until the network entrance. The vehicle remains stopped for $d_{\text{rt}} = 5$ min ($\text{driverResponseTime} = 300$ s), and then at time $t_{\text{to}} = 16$ 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.

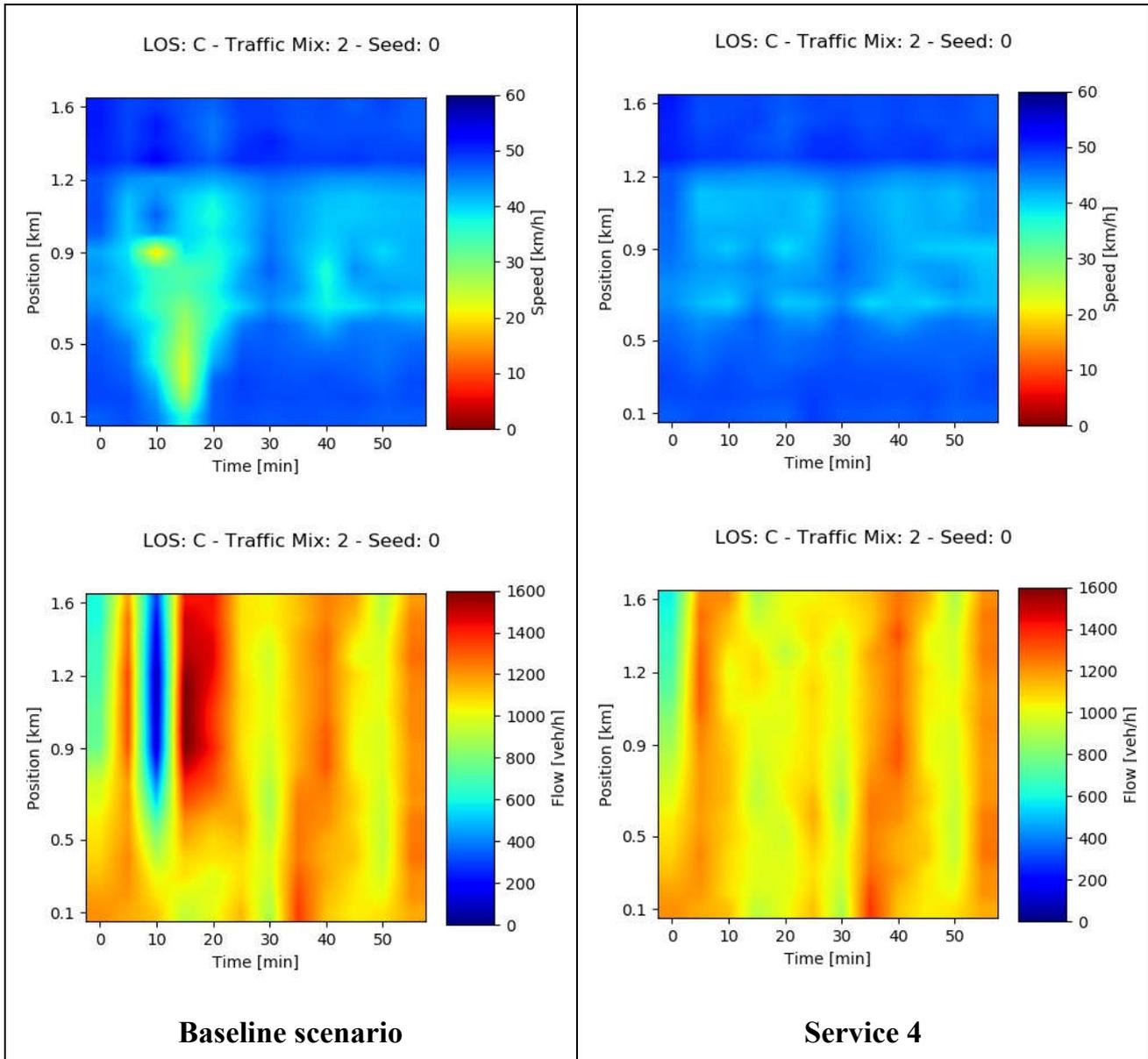


Figure 37: Example speeds and flows tempo-spatial diagrams for use case 4.2 (LOS C, vehicle mix 2, urban network). The left column corresponds to the baseline scenario and the right column to the traffic management (Service 4) scenario.

2.4.3.1.2 Impacts on traffic safety

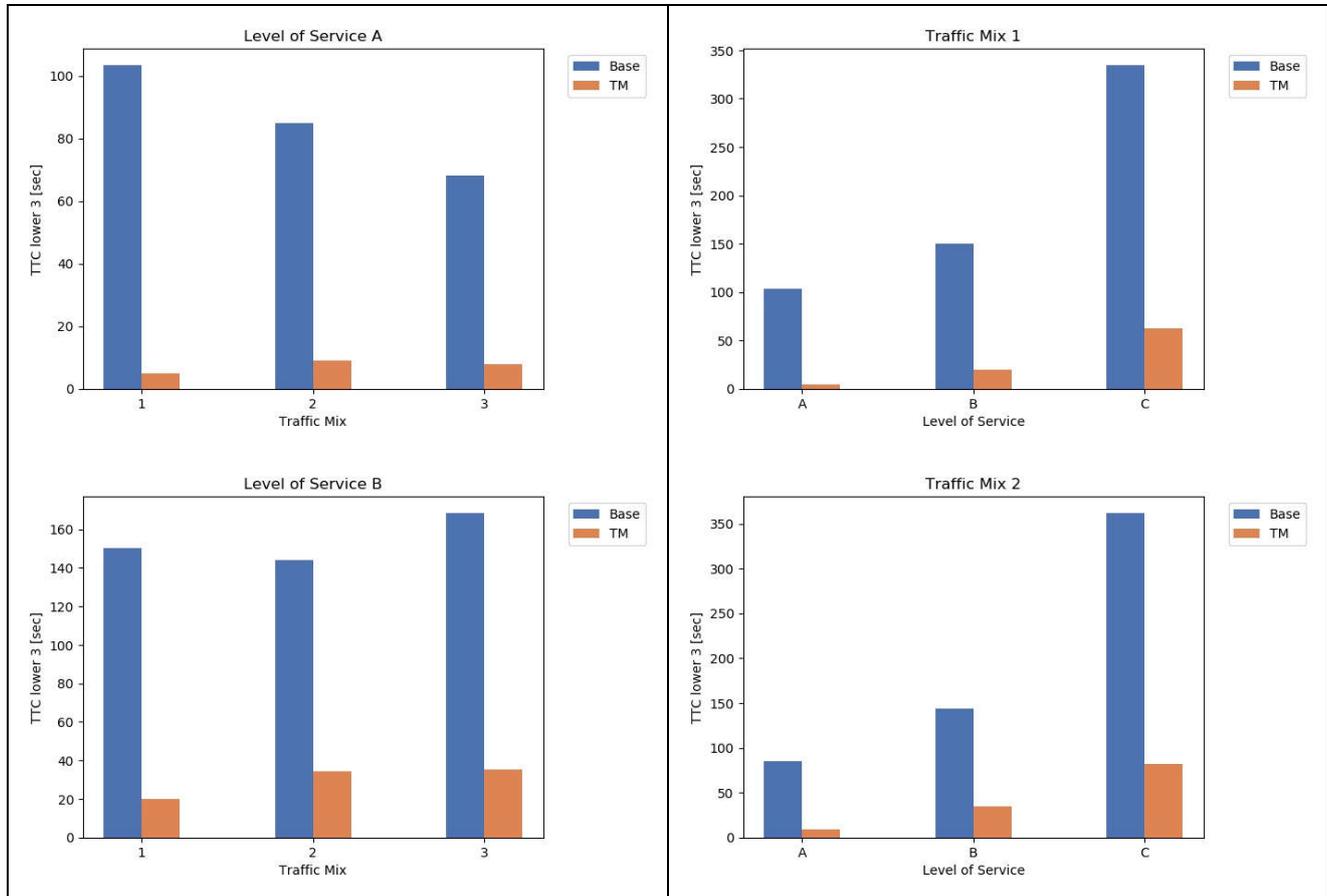
Figure 38 shows the average number of safety-critical events occurring for the examined simulation scenarios (traffic demand levels, vehicle mixes, traffic management case). Safety-critical events are assessed based on the TTC indicator within the context of this research. Vehicle interactions encompassing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



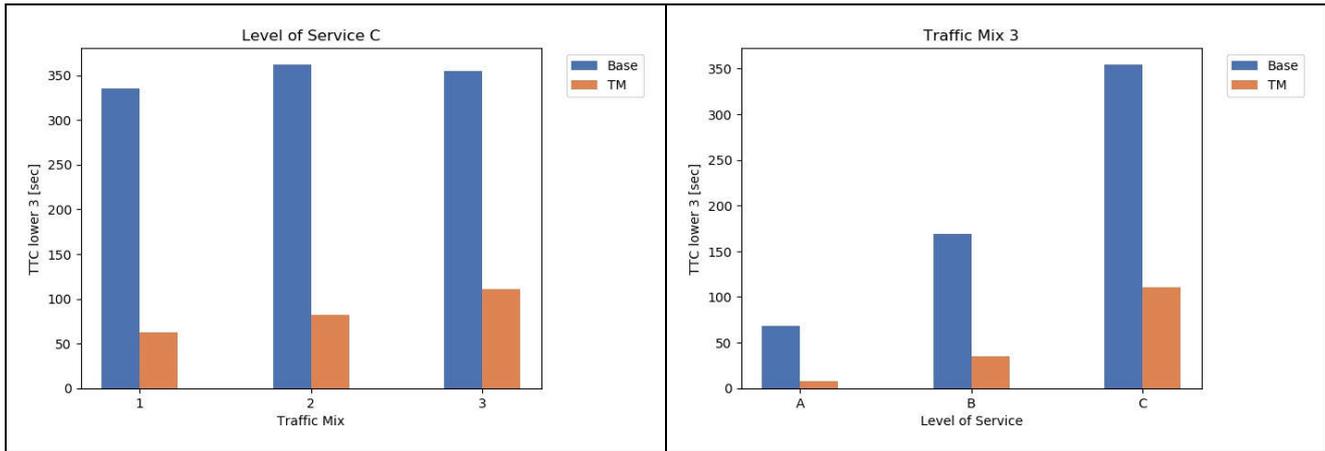
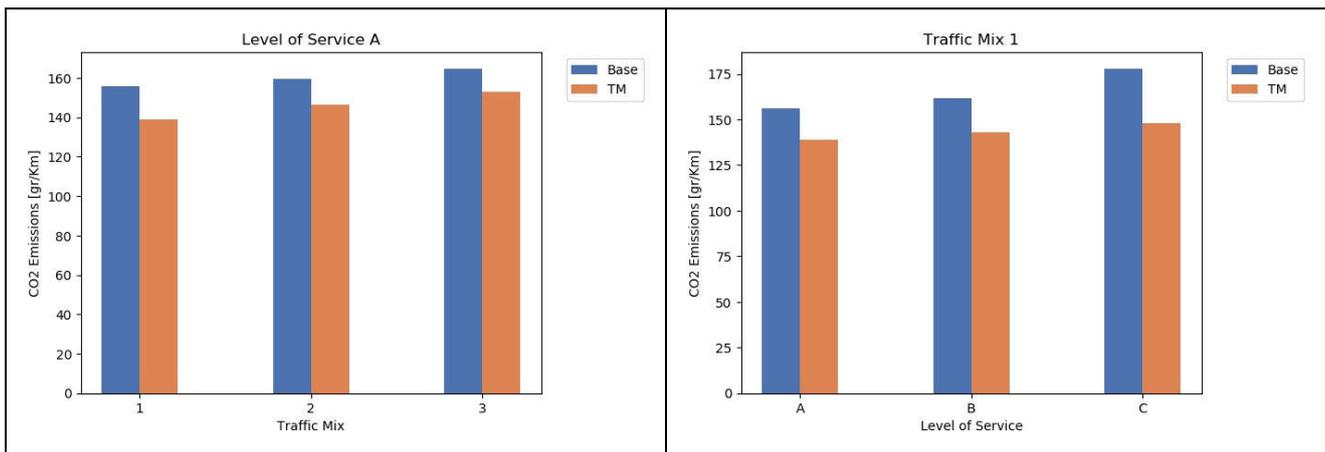


Figure 38: Average number of safety-critical events (TTC <math>< 3.0\text{ s}</math>) for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mix). Different bar colours correspond to baseline and traffic management simulations.

2.4.3.1.3 Environmental impacts

The environmental impacts of Service 4 on the urban network are assessed in terms of CO₂ emissions per kilometre travelled for the different traffic demand levels and vehicle mixes. CO₂ 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 CO₂ emissions reduction of approximately 18%. In general, CO₂ 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, CO₂ emissions do not significantly increase for higher LOS when Service 4 is implemented.



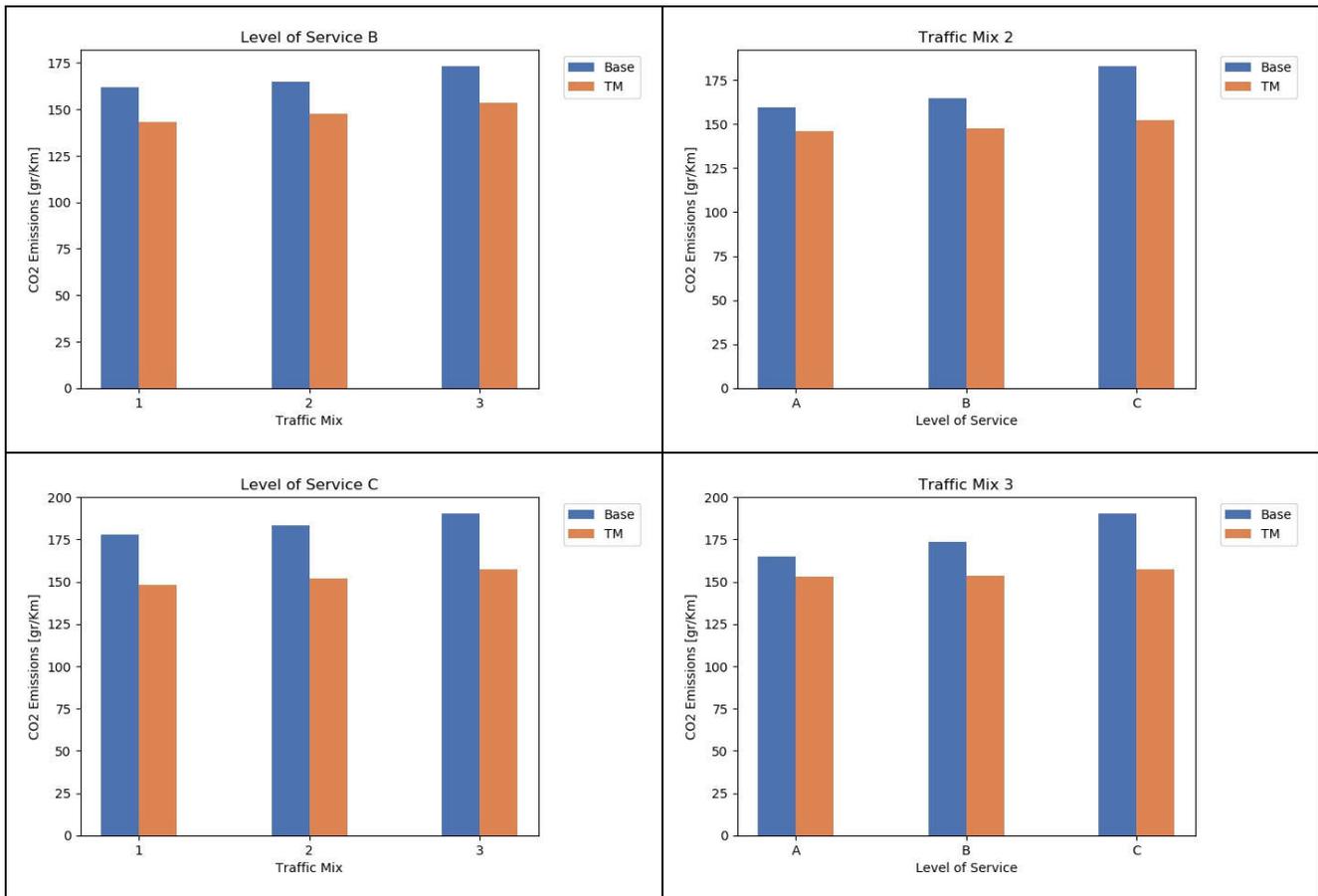


Figure 39: Average CO₂ emissions per kilometre travelled for use case 4.2 (urban network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

2.4.3.2 Motorway scenario

2.4.3.2.1 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)V's 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.

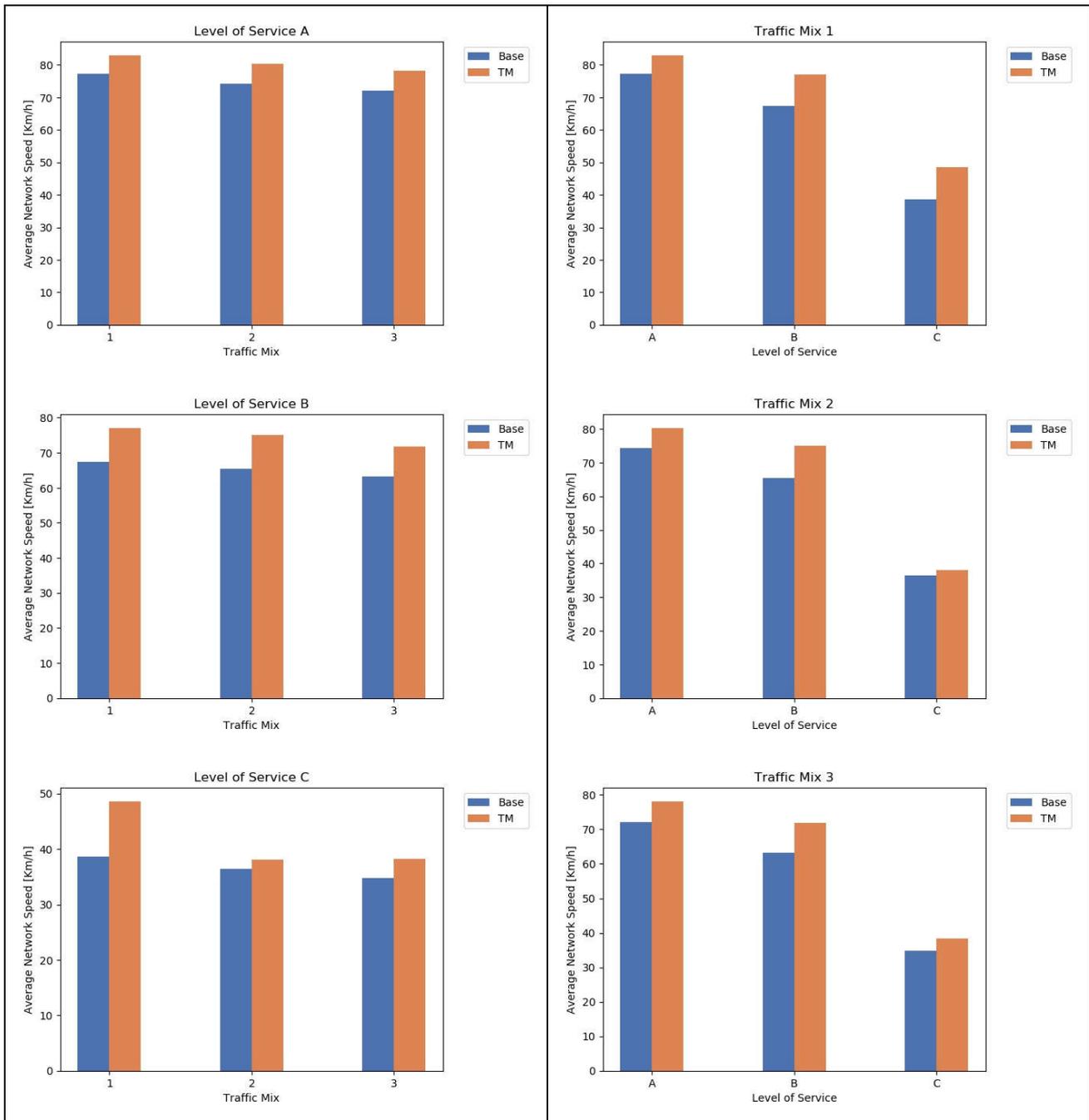


Figure 40: Average network speed for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

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.

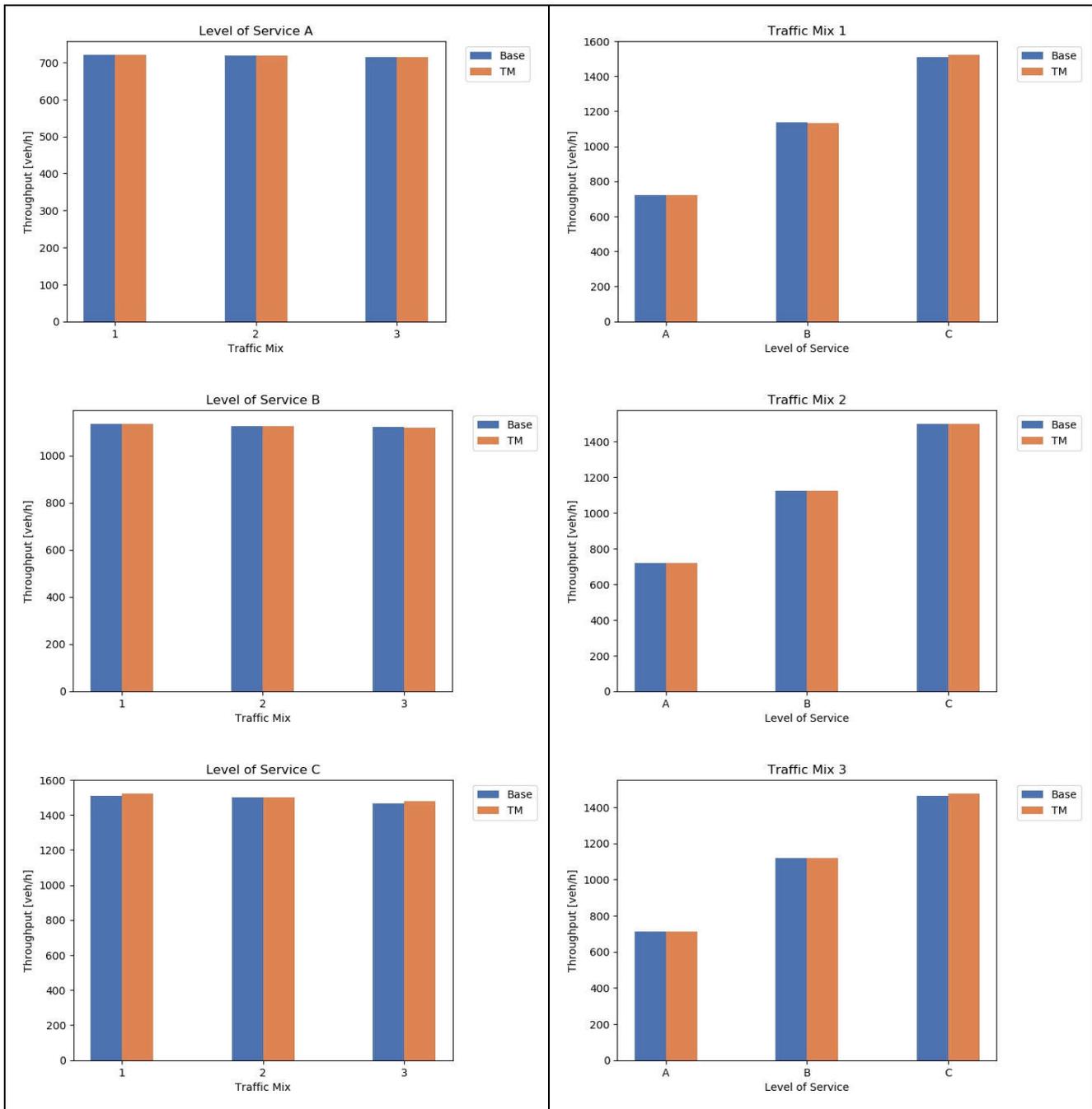


Figure 41: Throughput for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and vehicle simulations.

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.

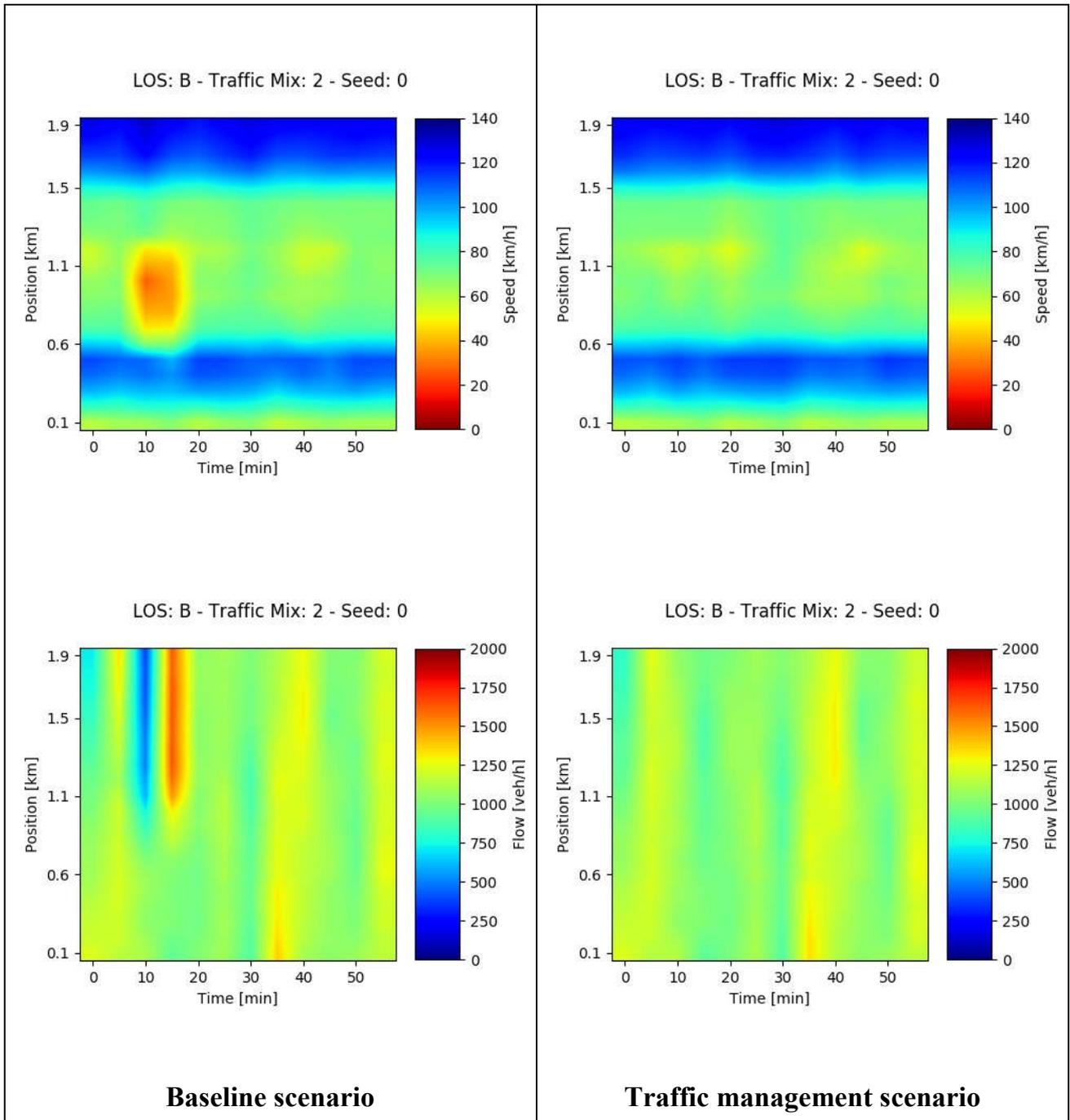


Figure 42: Example speed and flow tempo-spatial diagrams for use case 4.2 (LOS C, vehicle mix 2, motorway network). The left column corresponds to the baseline scenario and the right column to the traffic management (Service 4) scenario.

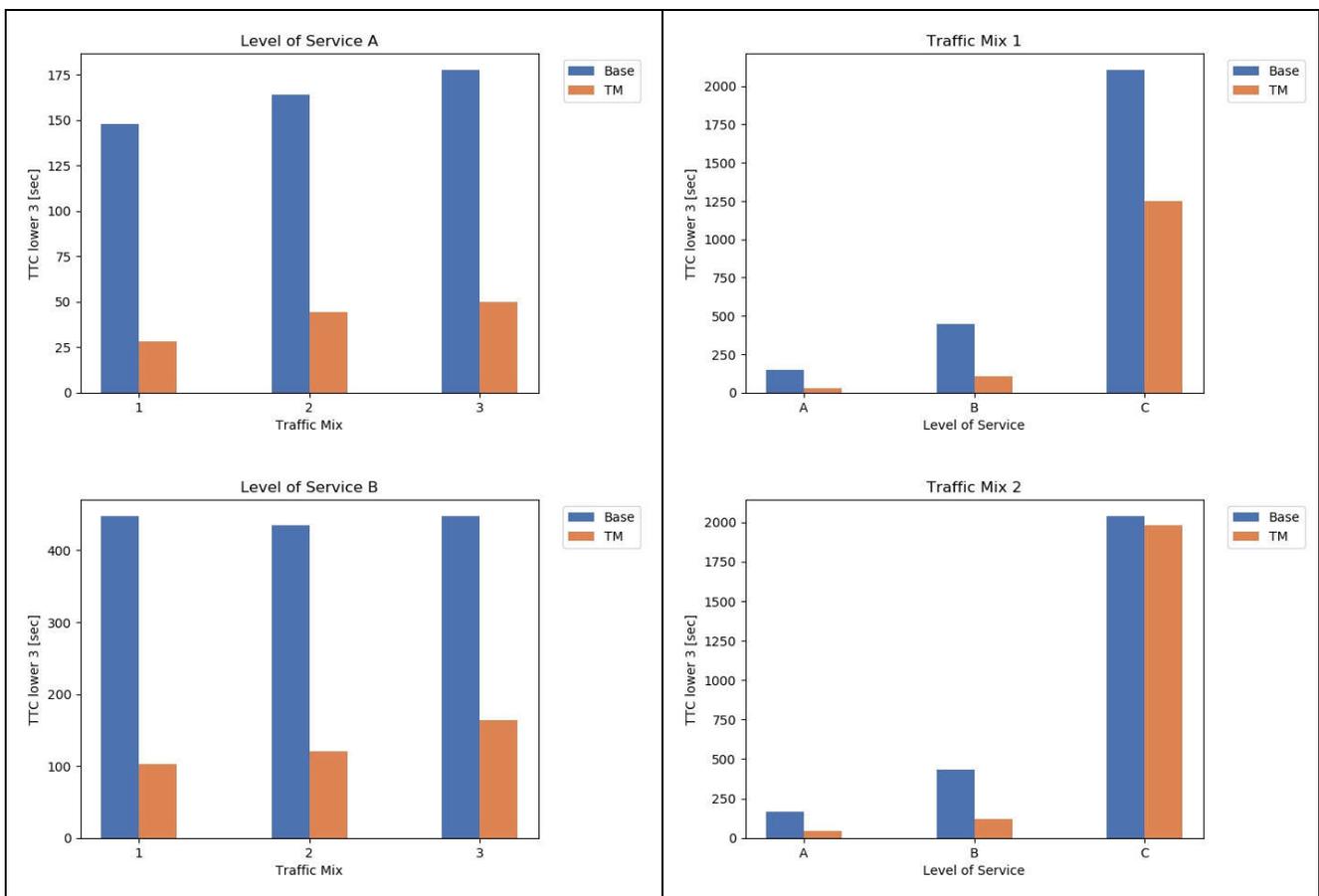
2.4.3.2.2 Impacts on traffic safety

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)V 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)V. 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.



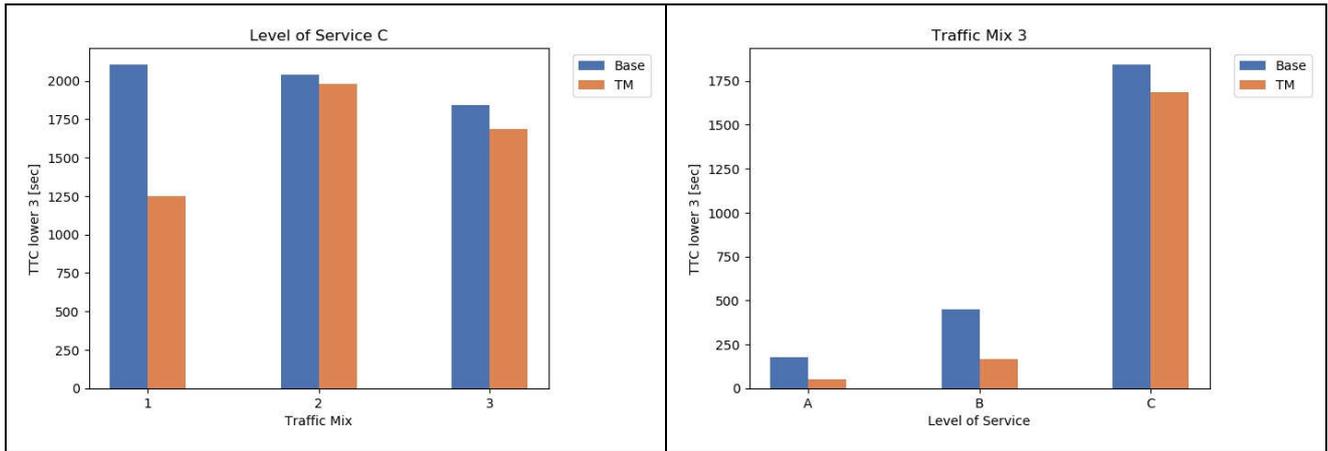


Figure 43: Average number of safety-critical events (TTC < 3.0 s) for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

2.4.3.2.3 Environmental impacts

The MRM guidance to the safe spot results in CO₂ 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, CO₂ 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 CO₂ emissions. Overall, CO₂ emissions benefits presented in Figure 44 are in accordance with the aforementioned traffic efficiency impacts (network-wide and local) of Service 4.

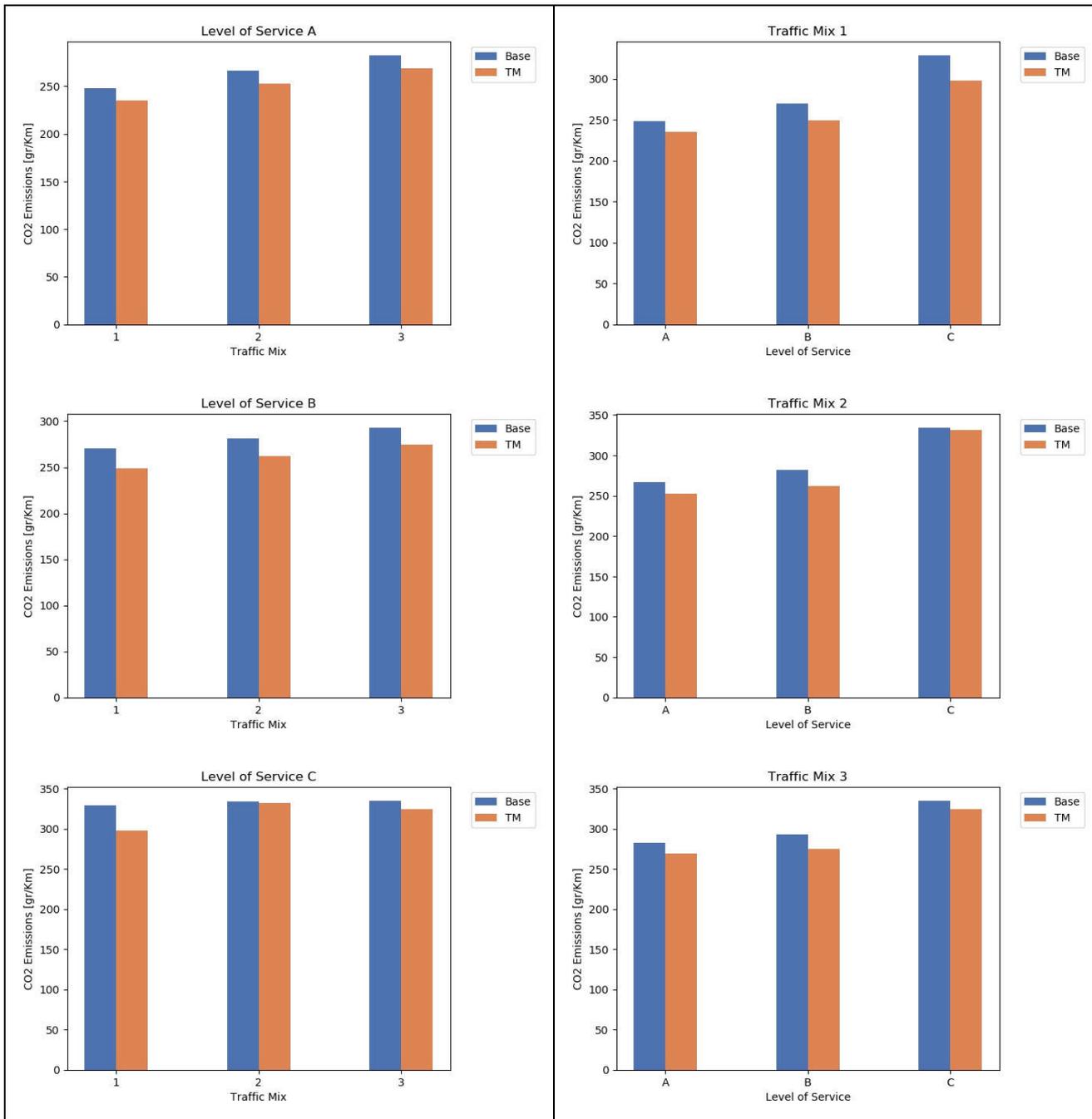


Figure 44: Average CO₂ emissions per kilometre travelled for use case 4.2 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

2.4.4 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 CO₂ 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.

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

2.5.1 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).

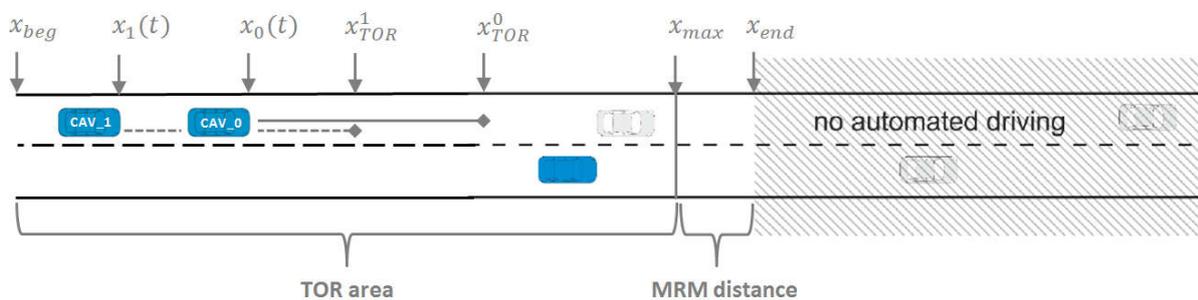


Figure 45: Schematic distribution area for TORs within a transition area.

2.5.2 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.

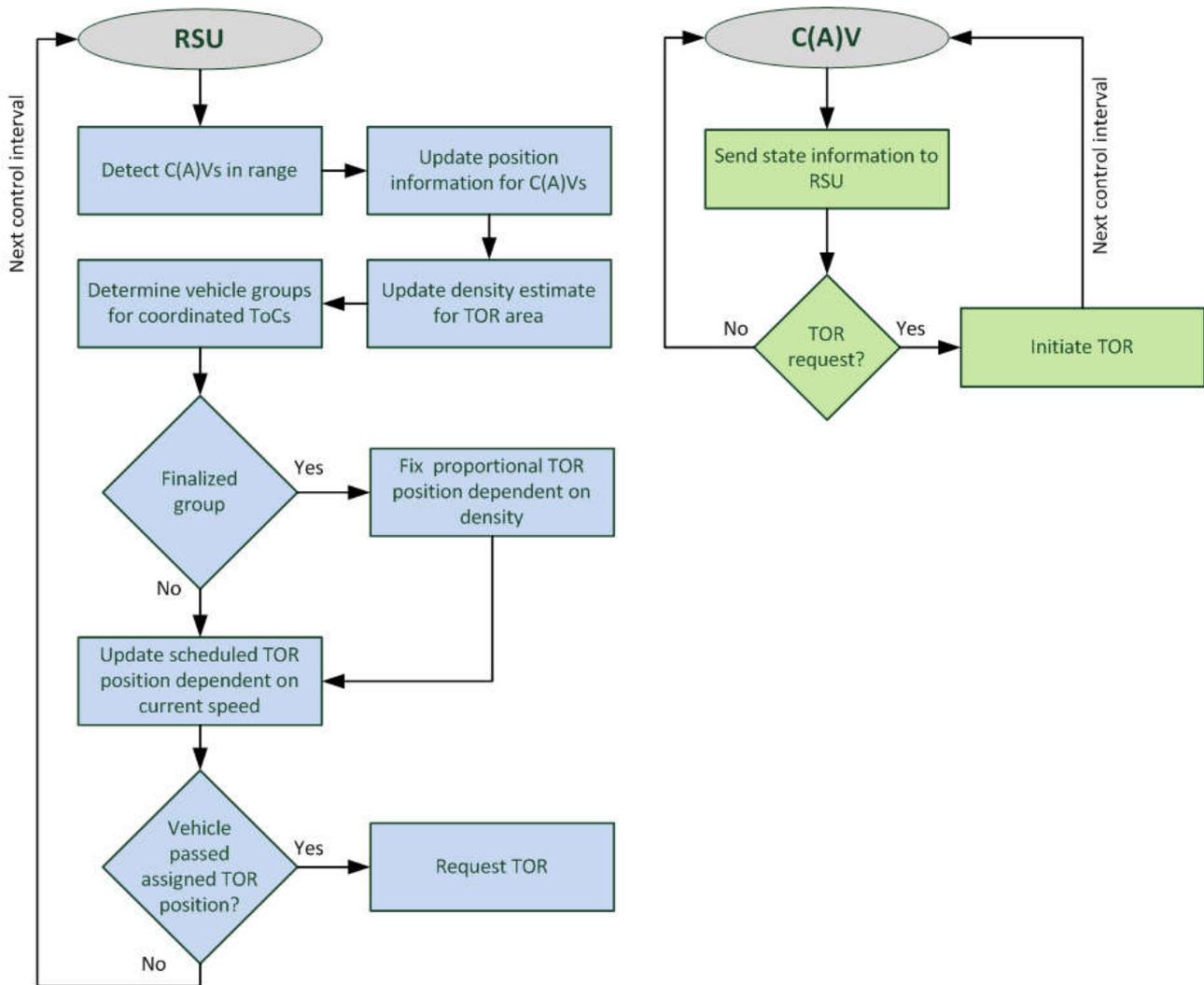


Figure 46: Traffic management service for use case 5.1.

2.5.2.1 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:

$$D_g = g_1 - g_A \tag{3}$$

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

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

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

$$g_A = SPACING_A + TIMEGAP_A * v(t) \quad (5)$$

Thus, the estimated maximal increase of the gap is:

$$D_g = g_1 - g_A = \frac{D_t^2}{2b} \quad (6)$$

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

$$D_t = \sqrt{2 * D_g * b} \quad (7)$$

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

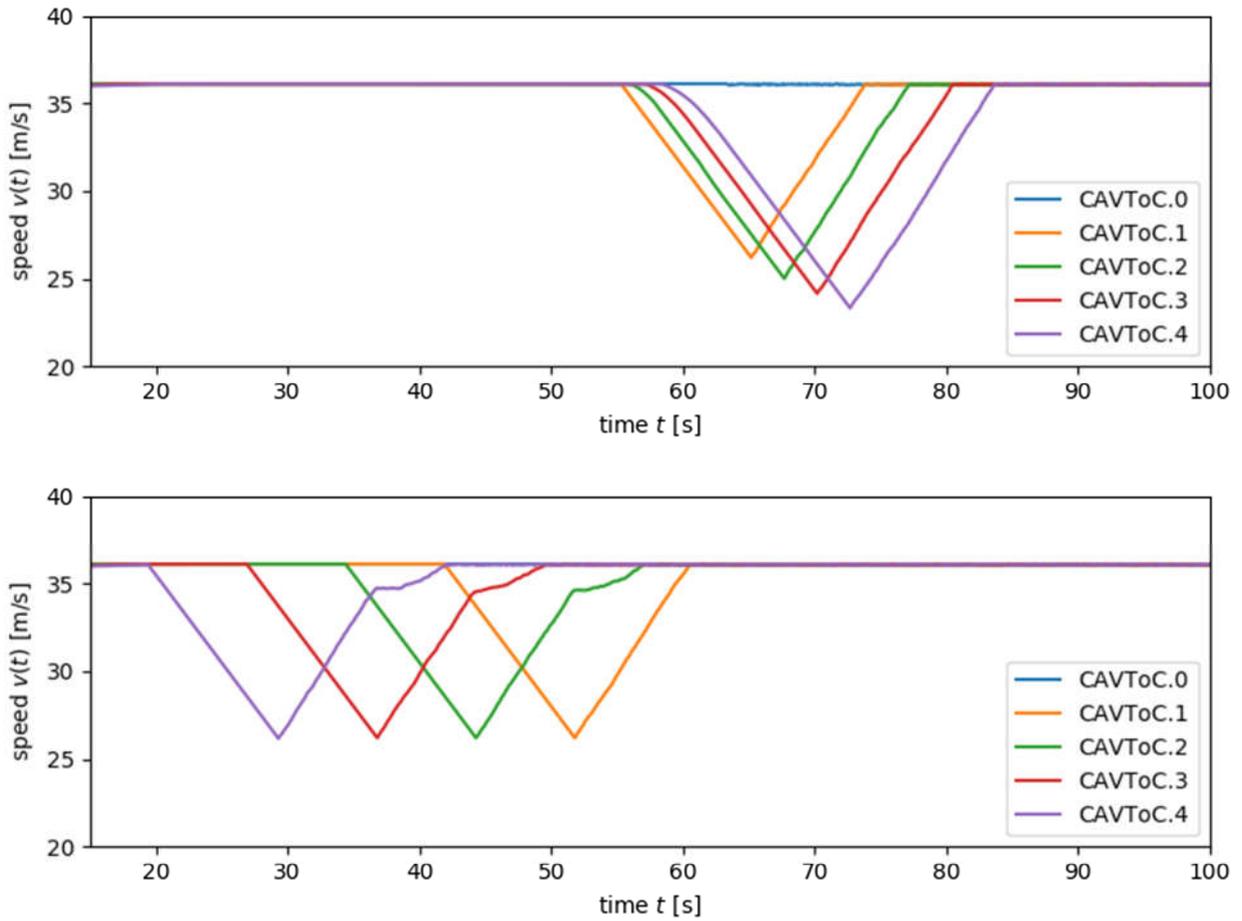


Figure 47: Speed runplots for different TOR scheduling approaches for a group of five CAVs. Upper panel: simultaneous TORs as frequently occurring in baseline case. Here issued at $t \approx 55$ s; Lower panel: distributed TORs starting with a TOR for the trailing vehicle with ID ‘CAVToC.4’ at $t \approx 20$ 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:

$$t_i = t_0 - i * D_t \quad (8)$$

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 $t_0 = \max\{0, (x_{\text{TOR}}^0 - x_0(t)) / v_0\}$ at a point x_{TOR}^0 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_{TOR}^0 scales linearly between these extremes in proportion to the renormalised downstream density $\rho(t)$:

$$x_{TOR}^0 = \min\{x_{max}, x_{beg} + \rho(x_{max} - x_{beg})\} \quad (9)$$

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. $x_{TOR} = x_{beg}$, for $\rho = 0$, it is scheduled for $x_{TOR}^0 = x_{max}$. Given t_i , from (8) we obtain corresponding TOR-points:

$$x_{TOR}^i = x_i + t_i * v_0 \quad (10)$$

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_{TOR}^i :

$$\theta_i = \frac{x_{TOR}^i - x_i}{x_{max} - x_i} \quad (11)$$

That is:

$$x_{TOR}^i = x_i + \theta_i * (x_{max} - x_i) \quad (12)$$

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

Parameters for the TM 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
SPACING _{TOR}	10 m	Assumed minimal spacing to be obtained by the open gap mechanism
TIMEGAP _{TOR}	2.0 s	Assumed minimal time headway to be obtained by the open gap mechanism
TIMEGAP _A	1.5 s	Assumed minimal time gap used by the automated car-following controller
SPACING _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

2.5.2.2 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/s². 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)V's do (for details on the model parameters see Deliverable D3.1).

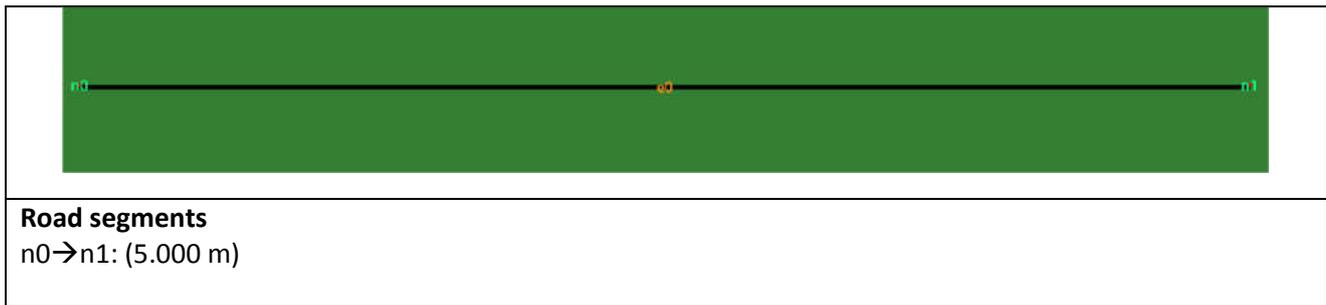
2.5.2.3 Baseline scenario adaptation

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		



2.5.3 Results

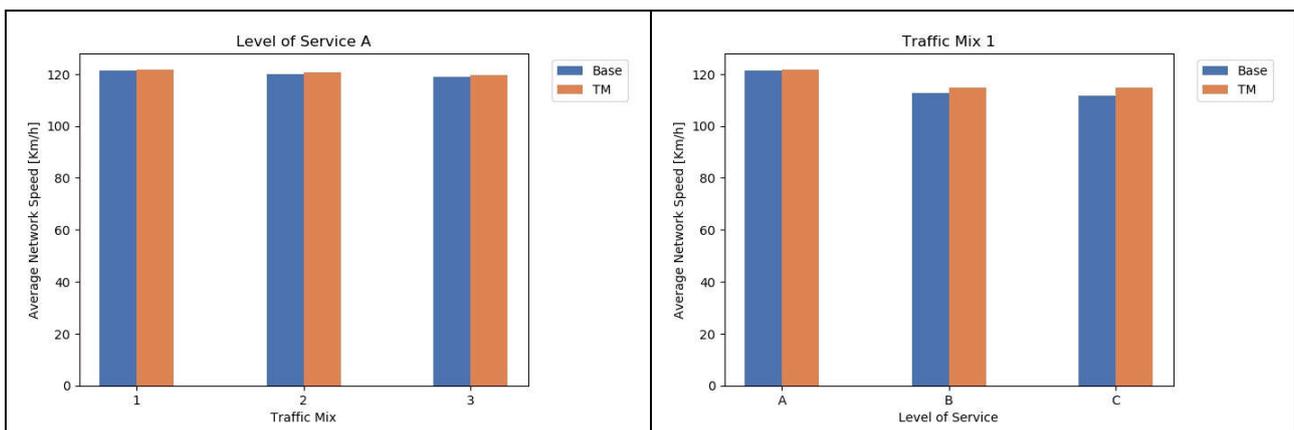
2.5.3.1 Impacts on traffic efficiency

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.



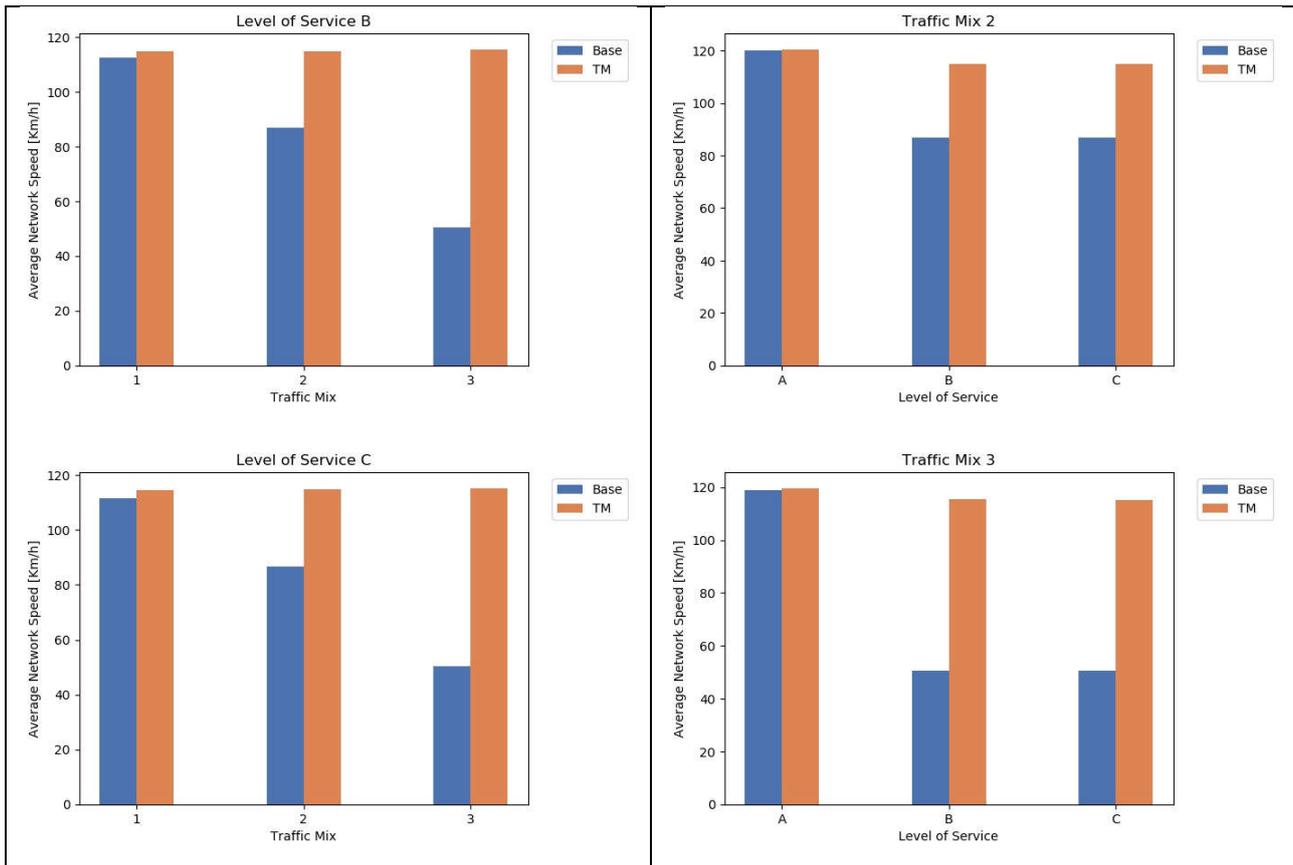
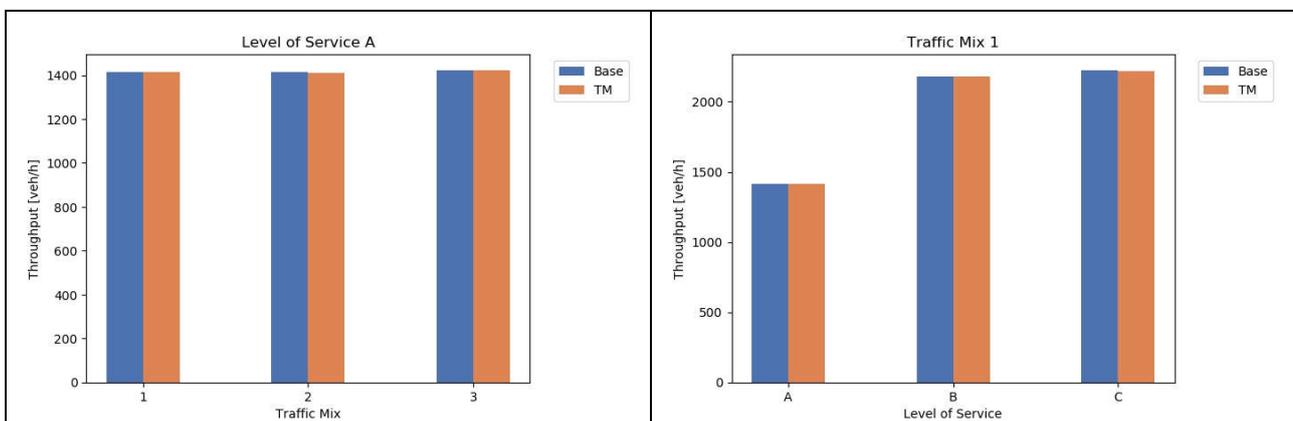


Figure 48: Average network speed for use case 5.1 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Figure 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.



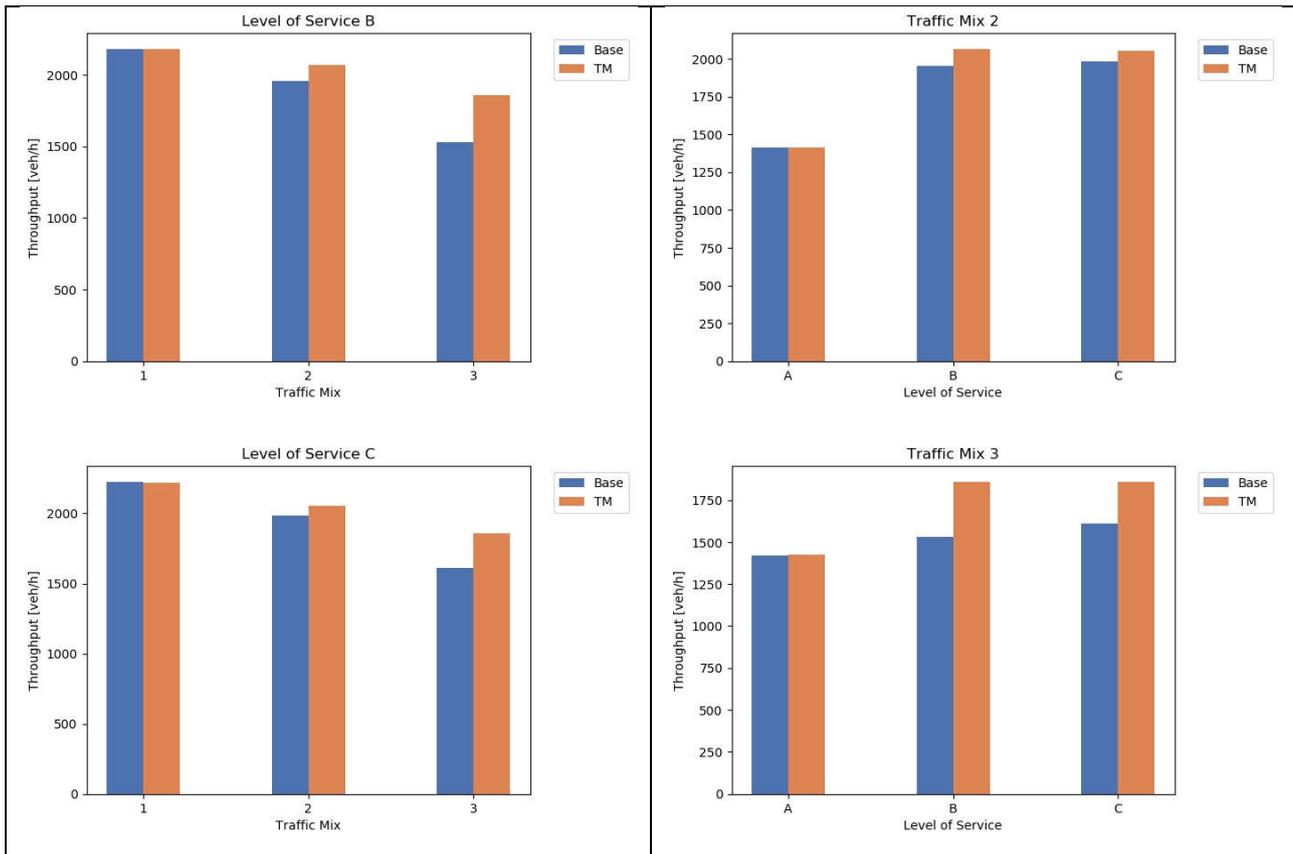


Figure 49: Throughput for use case 5.1 (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Local Impacts

Figure 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).

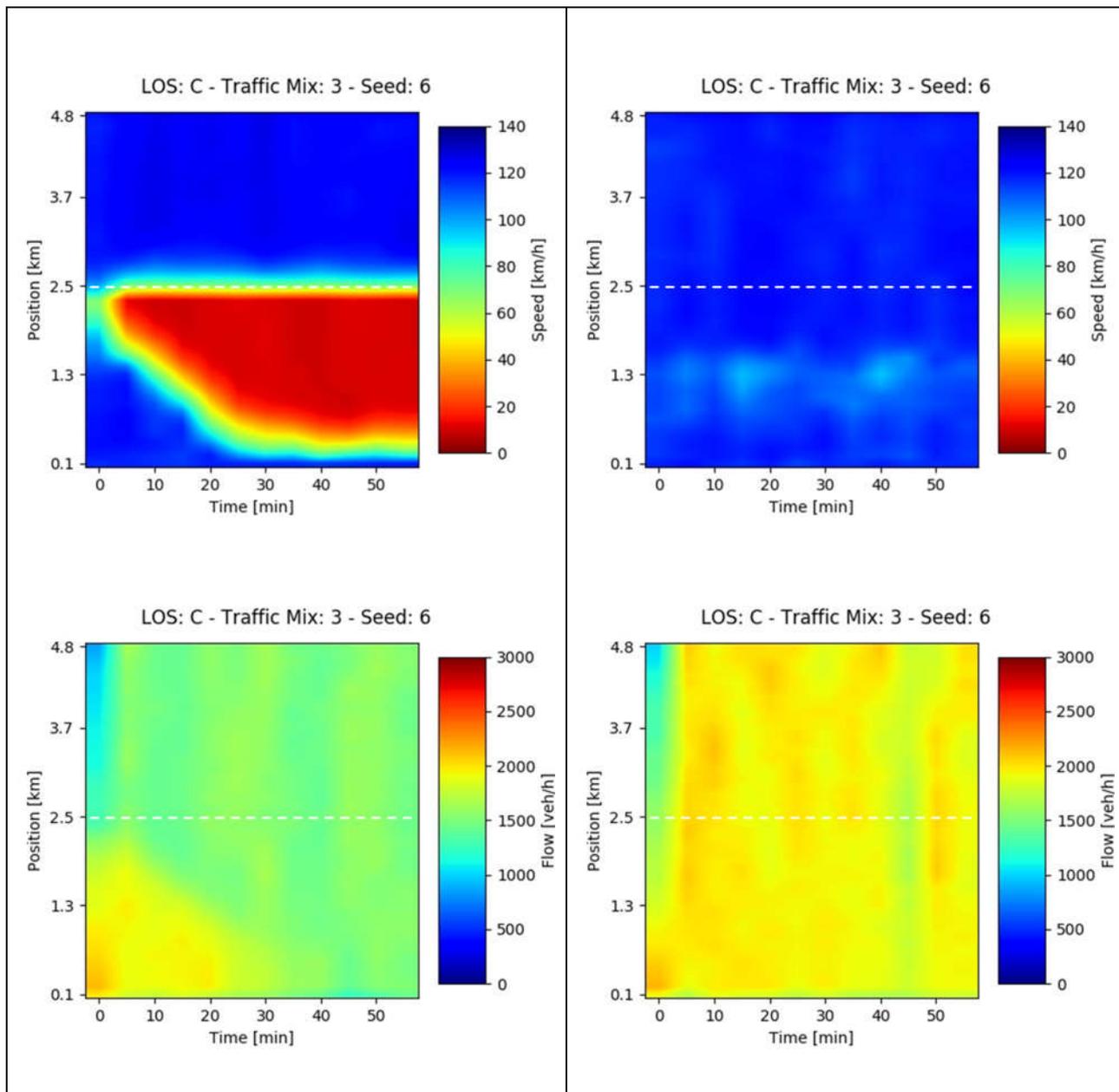


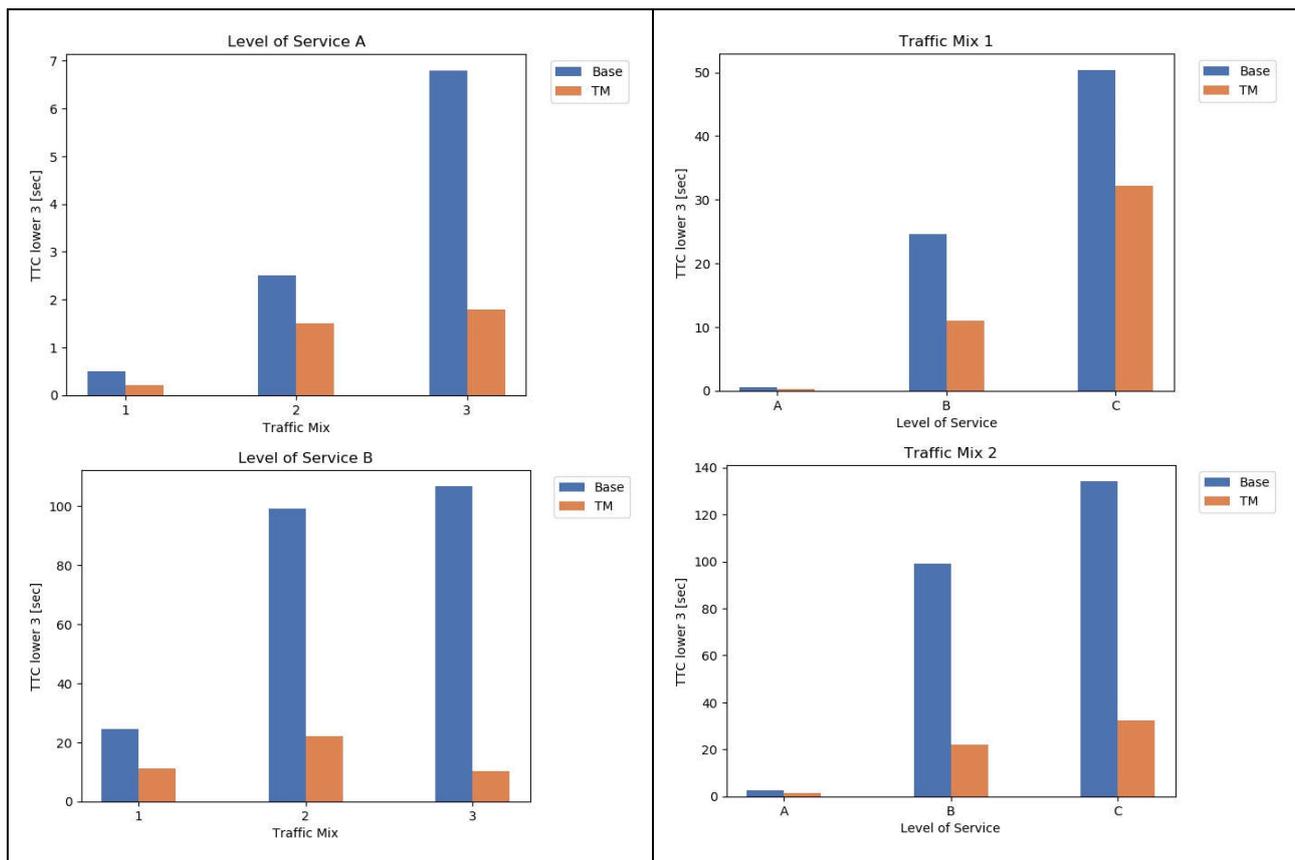
Figure 50: Example tempo-spatial diagrams for measured speeds (upper row) and flows (bottom row) for use case 5.1 (LOS C, vehicle mix 3, seed 6). The left column corresponds to the baseline and the right column to the applied traffic management Service 5 simulations. The white dashed line marks the entry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

2.5.3.2 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.



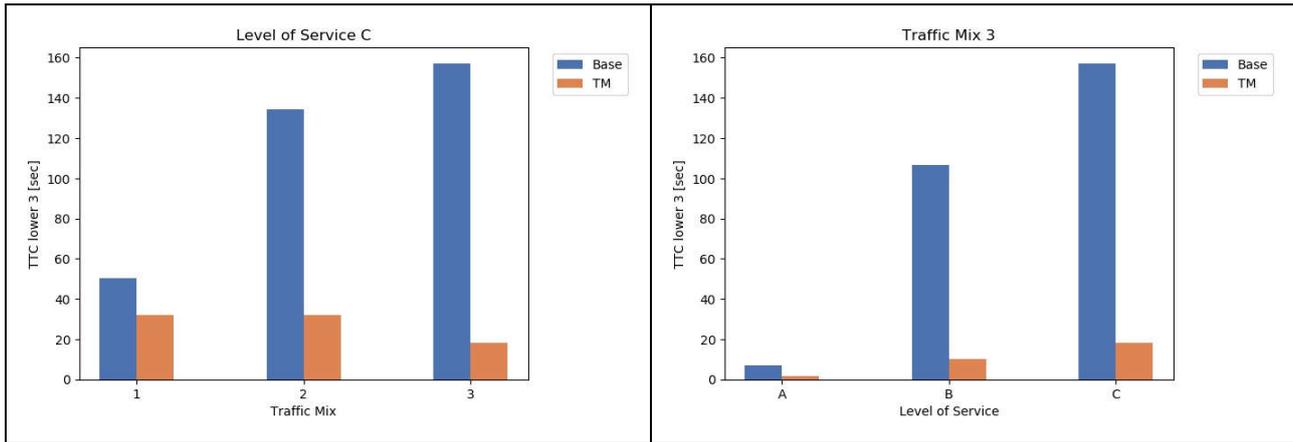


Figure 51: Average number of events with TTCs below 3.0 seconds for use case 5.1 (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

2.5.3.3 Environmental impacts

Figure 52 shows the average CO₂ 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 CO₂ emissions is not equal for every chart).

For the baseline simulations, the CO₂ 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 CO₂ emissions per kilometre driven do neither exhibit any significant variations.

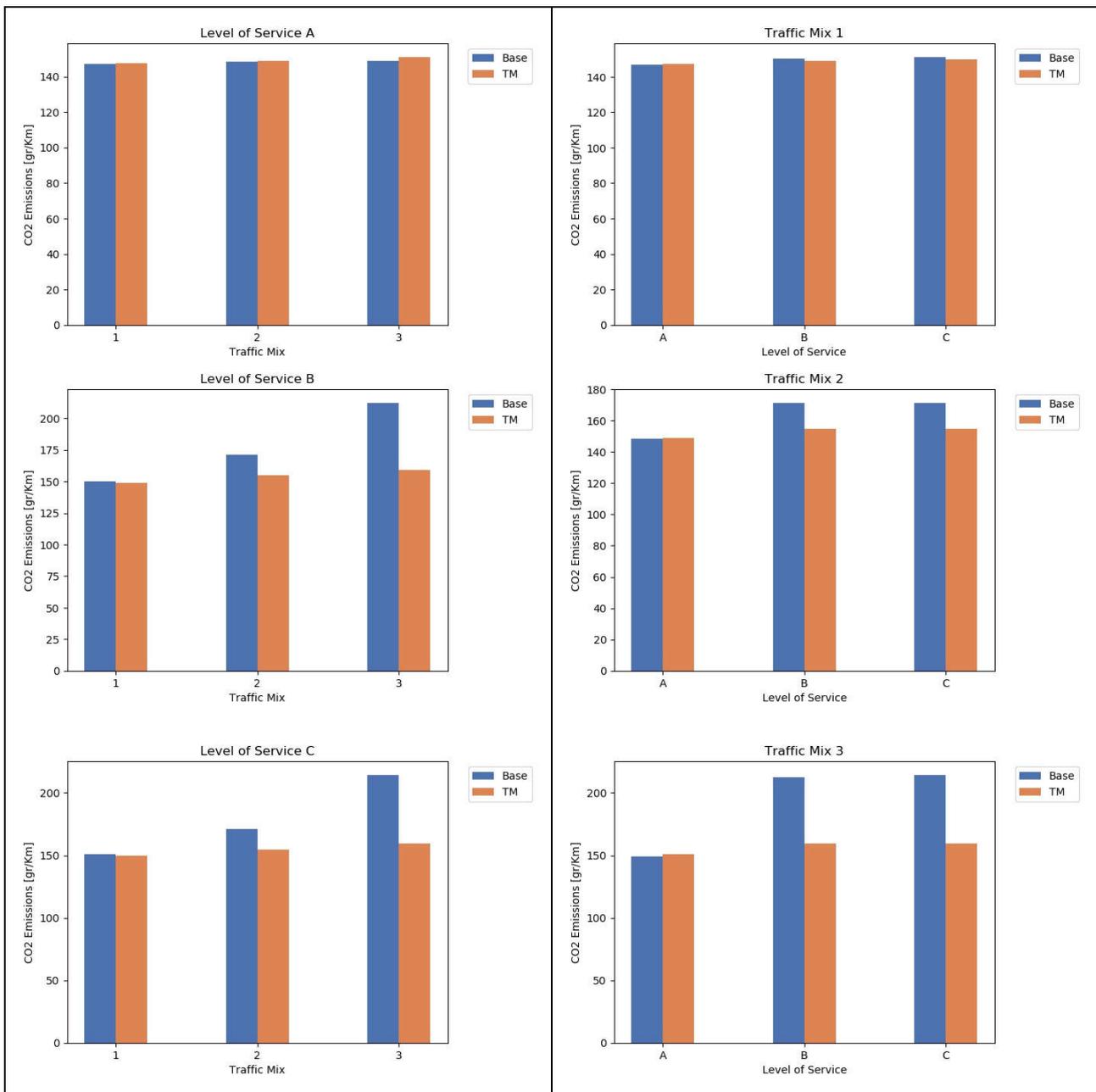


Figure 52: Average CO₂ emissions per kilometre travelled for use case 5.1 (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

2.5.4 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 CO₂ 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 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.

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5 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 14: 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 15: Classification of actors (vehicle types).

Class Name	Class Type	Vehicle Capabilities
Class 1	Manual Driving	<ul style="list-style-type: none"> – Legacy Vehicles – (C)AVs/CVs (any level) with deactivated automation systems
Class 2	Partial Automation	<ul style="list-style-type: none"> – 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	<ul style="list-style-type: none"> – (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	<ul style="list-style-type: none"> – (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 16: 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%	-	-