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**Motorway merging assistant for automated vehicles**

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**Abstract**

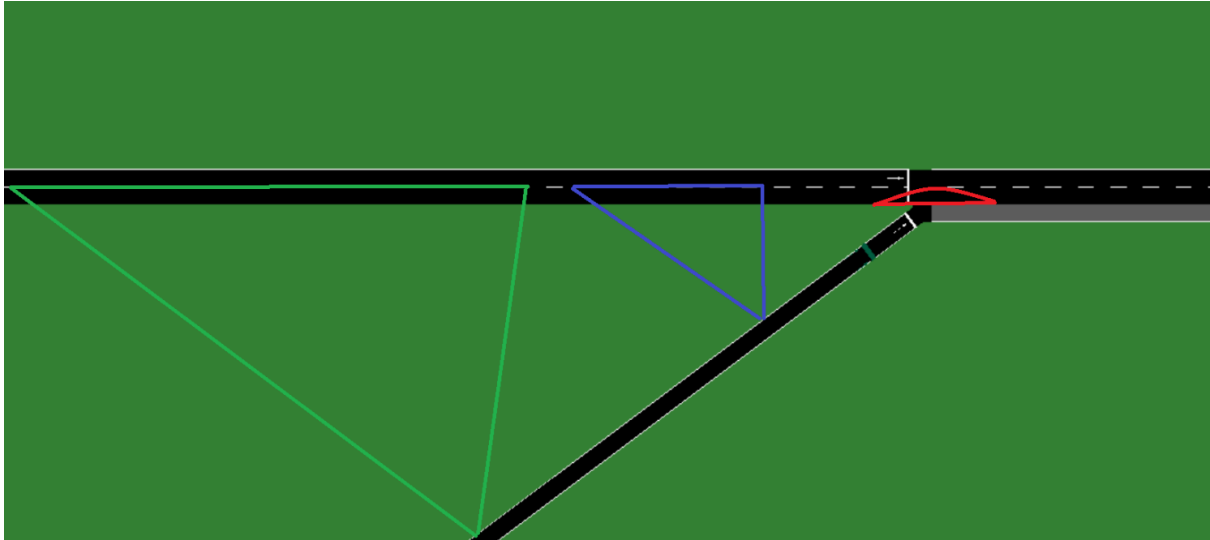
This research presents a motorway merging assistant for automated vehicles. Unlike work in contemporary research it does not require full penetration of cooperative vehicles to operate. An underlying model fusing data from legacy sensors, cooperative data and cameras builds an accurate view of the situation in order to cope with non-equipped vehicles. The system contains three measures: prohibition of lane change towards the outer lane on the main road, issue a ToC as soon as it can be concluded that a safe merge in automated mode is not possible and speed advice for guidance towards the first available gap. Results showed a reduction of required ToCs by up to 92%. A positive impact on traffic efficiency was observed with a reduction of stops by up to 87% and a CO<sub>2</sub> reduction of up to 7.3%. Safety was significantly improved by more than halving the number of increased risk situations.

**Keywords:**

Motorway, merging, traffic management

**Introduction**

Merging into the motorway is a routine procedure for human drivers. However, the area that can be taken into account for selecting a gap is limited for automated vehicles as is illustrated in Figure 1. The Automated Vehicle (AV) will only observe a small area at a late moment, so there is also not a lot of time for speed adjustment to target another gap. The human driver in a so-called Legacy Vehicle (LV) without infrastructure assistance can observe a larger area while being further away from the merging area. This means there is more time to adjust the speed to arrive at the selected gap when reaching the merging area. For a Cooperative Automated Vehicle (CAV), the infrastructure can already select a gap once the vehicle enters the on-ramp, long before there is visibility of the main road, allowing an even larger area to select a gap from. The merging assistant described in this paper will focus on giving speed advice to CAVs entering the on-ramp.



**Figure 1 - Decision area for gap selection for AV (red), LV(blue) and infrastructure assisted C(A)V(green)**

The work is part of the TransAID project[1], which develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of LVs, CVs and CAVs especially in the transition areas where CAVs have to hand over control to the driver. The approach is to prevent having to issue a Transition of Control (ToC) as much as possible and otherwise manage them in an efficient way. As a last resort, if the driver does not respond, a Minimum Risk Maneuver (MRM) can be executed.

### Literature review

Having a direct impact on the capacity drop of a motorway, merging areas have always been an important research topic. Most of these research are based on queuing theory and statistics that do not combine various information sources obtainable from communication-capable vehicles, such as Cooperative Vehicles (CVs) and CAVs. Therefore, contemporary ramp metering installations merely control the average capacity on a macro level, rather than actively trying to prevent causing a capacity drop on a micro-level. The most commonly used strategy is ALINEA [2], 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 regulator 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. The on-ramp volume will be adjusted with a time interval, which is usually between 20 to 60 seconds. This is a strategy on a macro level that requires the set point to be significantly below the saturation point. This is because the traffic flow is never exactly homogenous and a vehicle on the on-ramp can arrive during a particularly busy 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 saturation when using a micro model of the situation. This was already considered in research that takes a connected vehicle environment into account. In the 1960's [3] took a given optimal merging sequence and casted it into a linear optimal regulator problem, which is a common problem in control engineering. Later, the work in [4] used a two-layer system with heuristic rules to cope with the non-linear behavior of the vehicle behaviour. In [5] a further extension was made to actually calculate the optimal merging sequence. For [6] the problem of controlling the vehicles movement was solved by defining it as a simple isoperimetric problem, but again the work focusses on the vehicle control. The step to a decentralized solution is made in [7], but only uses the vehicles' own sensors without communication between them. Using a slot-based approach [8], a high traffic efficiency can be achieved. The work in [9] has two concepts for ordering the vehicles: First In First Out or based on arrival order at the merging point. All these works have in common that all vehicles are controlled, by either directly controlling their speed and path or by assigning a slot in which they can travel. This means a 100% penetration of the technology is required, which is not sufficient for TransAID that deals with mixed traffic in various compositions of LV, CV and CAV.

For vehicle behaviour, two aspects need to be considered, longitudinal and lateral (lane change) behaviour. For the longitudinal behaviour, [10] presents 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 improving traffic flow. For the lateral behaviour, the first framework developed for lane changing is still used nowadays. It is Gipps' model [11]. 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' maximization 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 minimize 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 [12]. The work in [13] presents a more sophisticated merging model for mandatory lane change. This model introduces a unified

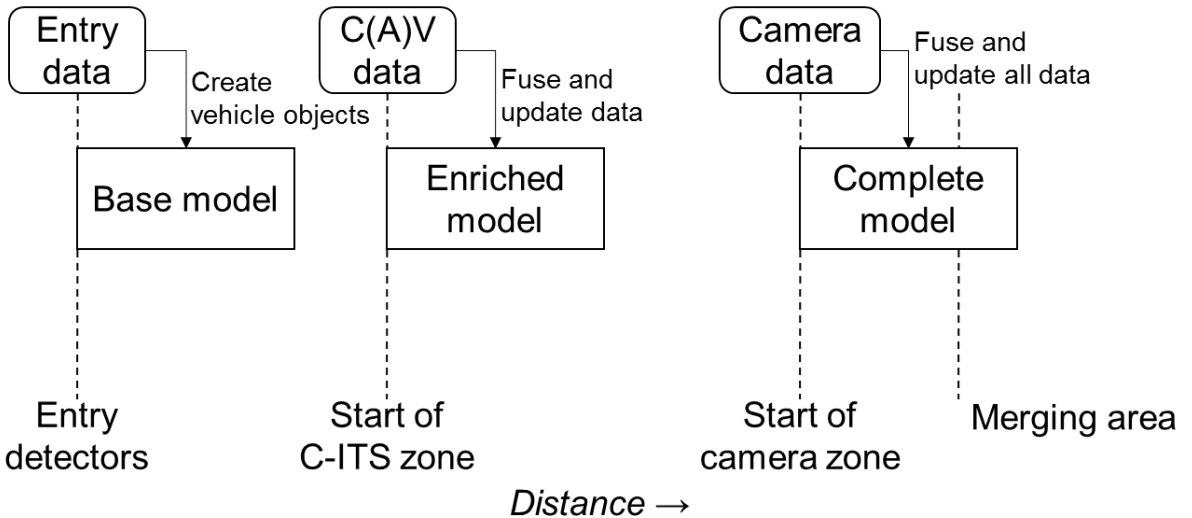
decision framework for drivers with latent plan. However, it searches for gaps that are currently present close to the vehicle and does not plan for merges far in advance.

This 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 a mixed traffic environment. In this way, the benefit of the increased search space as indicated in Figure 1 is maximized. 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. The used simulation models build on the work of [10-13] for realistic behaviour.

**Merging algorithm**

As already explained in the introduction, 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 closing in at the main road. Therefore, it can very well be 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 at a safe distance that still allows the ToC and a potential MRM if the driver does not assume control in time. This point is called the Merge Decision Point (MDP), which is also the target for the algorithm where the vehicles should merge. Using a speed of 100 km/h, the position of this MDP is at 435m from the end of the onramp according to the methodology of [1].

To be able to monitor the large area that is indicated in Figure 1, a model of the traffic situation is essential. The model designed to support the merging assistant takes three data inputs and fuses them according to a certain hierarchy. This is illustrated in Figure 2:



**Figure 2 – Traffic model for merging assistant**

The model starts with data from traditional sensors that can measure speed and occupancy. Once a vehicle leaves such a sensor, it is processed as an entry for the model. Then every time step the vehicle is moved closer to the merging area according to its speed, keeping constraints of minimum following distance into account. A major problem with this model is that the speed is assumed constant, while in reality especially human drivers vary their speed. Therefore, once C(A)V's get in range of the RSU and CAM messages with speed and position data are received, corrections can be made to the model. The position of the C(A)V is compared to the positions of the vehicles in the base model and the closest is selected and flagged as C(A)V for data fusion purposes. Then the speed and position is updated for CVs, while the current lane and the distance to the surrounding vehicles can also be updated for CAVs. Especially the relative distance to other vehicles is interesting to acquire data about unequipped LVs. As a last step a tracking sensor is used to monitor the situation close to the merging area. This sensor has information on speed, position and current lane for all vehicles and will therefore give a complete model. This sensor is, however, expensive to install and maintain, so it is only used in the area where it is really necessary. With higher penetration rates of C(A)V's the sensor is probably not required anymore. The current state of the model can also be taken to generate predictions for the future, which is exactly what is required to give a speed advice.

In line with the two options presented in [9], the estimated time to reach the MDP is chosen as a basis for the optimization target instead of distance to reach the MDP, because having two equidistant vehicles doesn't necessary mean that their trajectories are conflicted. So rather than a First In First Out (FIFO), a First Arrive First Out (FAFO) principle is used. This means an underlying model should determine the time to reach the MDP and from that the Merging Sequence (MS) and the insertion gaps can be determined. However, determining the MS according to the FAFO 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 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. If no suitable gap can be found in the underlying model, a ToC has to be issued. The following measures are used in this hierarchy:

- *Prohibit lane change from inner lane*

Since vehicles have to merge to the outer lane, it is beneficial to have less traffic here and vehicles from the inner lane should not go here close to the onramp. It is also detrimental to the traffic model quality.

- *Merging guidance with speed advice*

The core strategy is to provide guidance to vehicles on the on-ramp, as this has minimal impact to the main road. In this research a minimum speed advice of 60 km/h is used and a maximum equal to the speed limit of 100 km/h.

- *ToC and MRM fallback*

This measure monitors the situation and issues a ToC as soon as it can be concluded that no suitable gap can be found for a CAV to merge into anymore. The earlier this is issued, the more time the human driver has to prepare for a safe manual merging operation. This can happen straight at the start of the onramp in heavy traffic. Another possibility is that model inaccuracies are corrected closer to the merging area and result in a previously predicted gap to disappear,

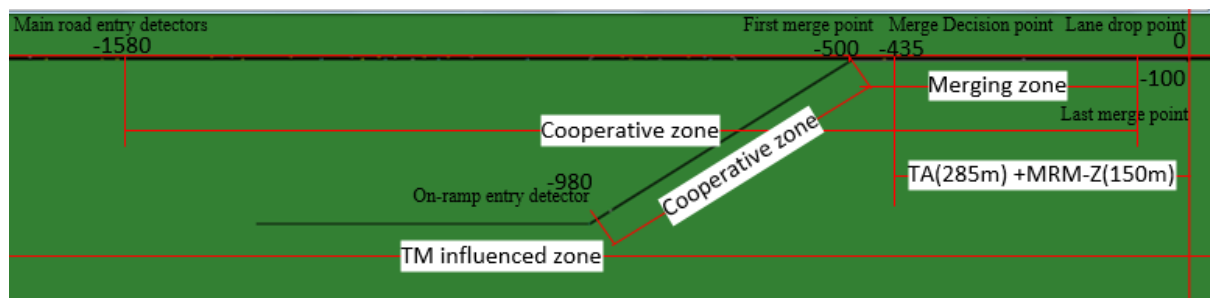
Traffic management calibration should of course determine the parameters of what an acceptable gap is and which speed advice range is acceptable. The speed advice range also results in constraints to the detection field. If a vehicle on the onramp would get the minimum speed advice ( $v_{MIN}$ ), there should already be data about vehicles on the main road who would arrive at the same time at the merge decision point with the maximum speed ( $v_{MAX}$ ). This means the detector distance for the entry detection on the main road ( $d_M$ ) should be larger than on the onramp ( $d_r$ ) according to this inequality:

$$\frac{d_M - MDP}{v_{MAX}} \geq \frac{d_r - MDP}{v_{MIN}} \quad (2)$$

Lastly, the merging assistant keeps track of all previously issued advice and propagates it into the model. This means that two vehicles cannot target the same gap if it's not sufficiently large for them to merge together.

**Simulation methodology**

A figure of the simulation network in SUMO [14] is shown in Figure 3. It is a synthetic network that represents an average motorway merging situation. The network has 500m sections before the entry detectors in order for traffic to reach the detectors in a free flow state, because some vehicles get injected too close to another and the traffic first needs to normalize.



**Figure 3 – SUMO simulation network overview**

All distances are shown relative to the end of the merging zone. The key parameters used for the simulation are summarized in Table 1:

**Table 1 – Simulation parameters**

Parameter	Value	Description
Main road detector distance	-1580 m	Both are chosen in accordance to inequality (2) and keeping into account that the detection takes place when a vehicle leaves the loop.
On-ramp detector distance	-980 m	
Camera detection distance	-600 m	Sufficiently in advance to issue ToC on time, but also capable to still see MDP with the same sensor.
Minimum gap	2.8s	The minimum gap between putative leader and follower required for selecting it as guidance target.
Maximum speed	27.78 m/s	Maximum advice speed, effectively defines the start of the search space for a gap.
Minimum speed	16.67 m/s	Minimum advice speed, effectively defines the end of the search space for a gap. Should be a safe speed to keep with human drivers around.
Merge Decision Point (MDP)	-435 m	Target point for the advice and also last possible distance to issue a ToC with the possibility of doing an MRM afterwards.

When evaluating inequality (2), the main road traffic takes at least 41.2s to reach the MDP, while the onramp traffic takes at most 32.7s. This means that the entry detectors could have been -1345 m and still satisfy the inequality. It would increase the accuracy of LV modelling as their positions were determined closer to the MDP. However, in real-world conditions it's most cost-efficient to use pre-existing detectors and they are not located at the most ideal position for the merging assistant. Therefore, some extra distance results in a more realistic situation. The minimum time for onramp traffic to reach the MDP is 19.6s, and therefore the search space is 13.1s.

The traffic volume for different Levels Of Service (LOS) is shown in Table 2. It should be noted that these are input levels and therefore, the volume after the lane drop is close to capacity at 1928 veh/h/l, which is 0.96 demand/capacity ratio. For all simulations 10 runs with a different random seed were carried out. More details on the car following and lane change models as implemented in SUMO can be found in [15].

**Table 2 – Traffic demand for different LOS**

Facility Type	Capacity (veh/h/l)	Level of Service (LOS)		
		A	B	C
On-ramp (100km/h)	1650 veh/h/l	462	726	1056
<b>Intensity (demand volume)/Capacity (IC or VC) ratio</b>		0.28	0.44	0.64
Motorway (100 km/h)	2000 veh/h/l	600	960	1400
<b>Intensity (demand volume)/Capacity (IC or VC) ratio</b>		0.3	0.48	0.7

For each traffic demand scenario, three combinations of measures will be simulated. The first is the baseline that only evaluates based on the vehicle sensors up to the MDP if the vehicle can merge and otherwise issues a ToC. The second has the full model operational as described by Figure 2 and issues

ToC, when it can already conclude that the vehicle will not reach a gap before the MDP. The last also adds speed advice and therefore has the full functionality of the merging assistant. Lastly, the percentage of LV, CV and CAV is also varied, with the share of C(A)V increasing with each mix:

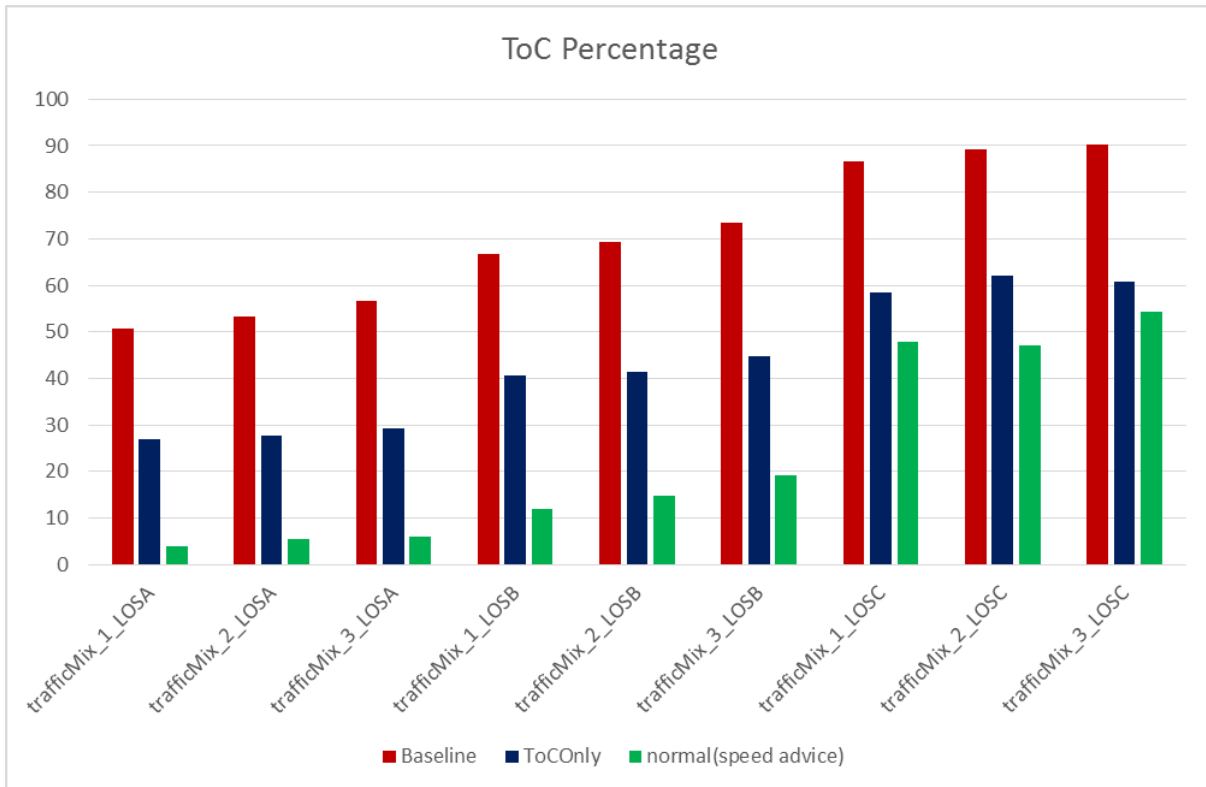
Mix 1: 70% LV, 15% CV and 15% CAV

Mix 2: 50% LV, 25% CV and 25% CAV

Mix 3: 20% LV, 40% CV and 40% CAV

**Results**

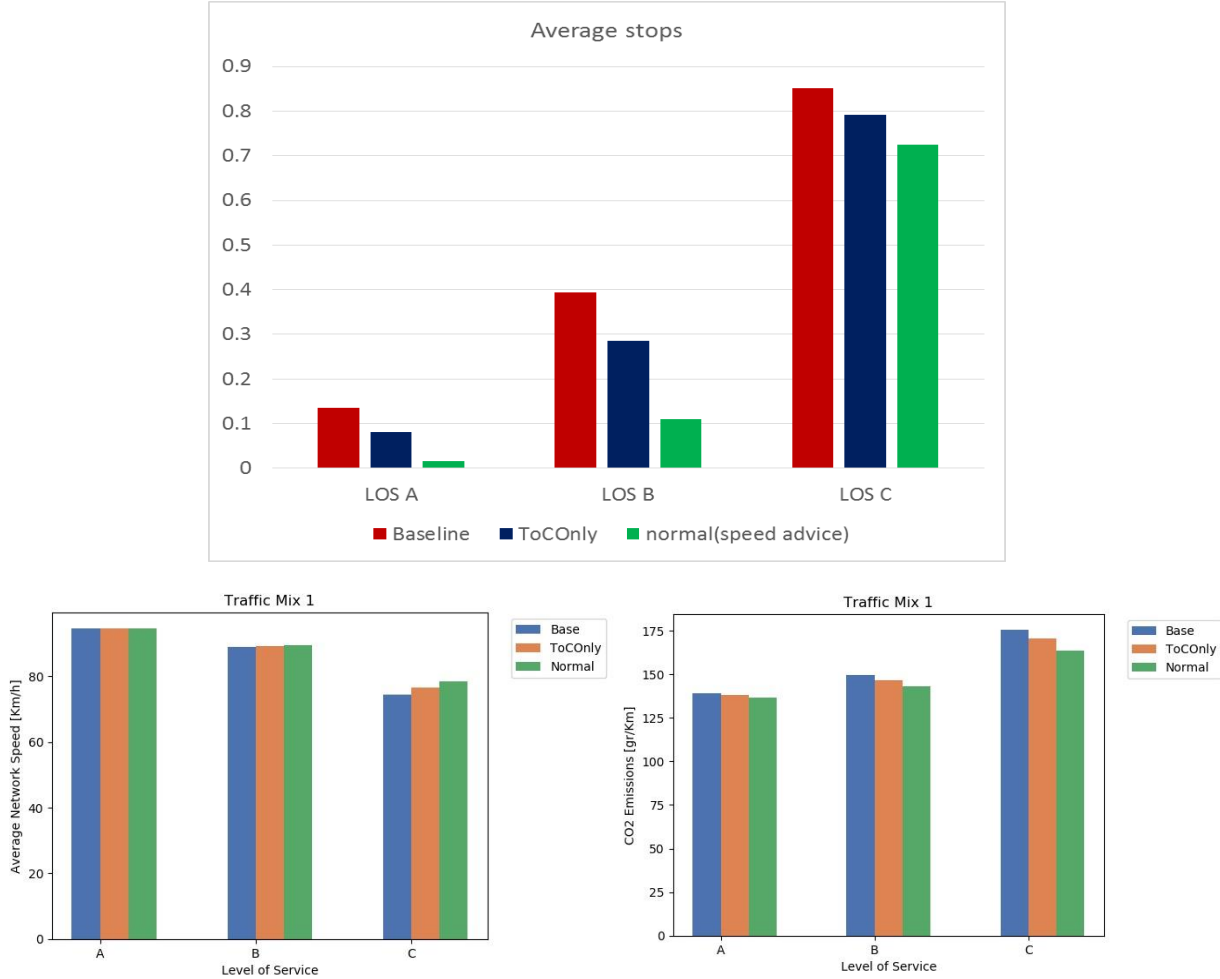
As the main goal of the research is to prevent ToCs, this is the first indicator that was analysed. The ToC percentage for the different scenarios is shown in Figure 4. It is clear that at any LOS the ToC-Only scenario outperforms the baseline and that the speed advice outperforms the other two. With increasing traffic intensity, the amount of ToC required is with a percentage around 50% still quite high. The standard deviation between the runs was usually around 2%, except for the speed advice scenario with LOS C, which was 10%. This is an indication that the traffic volume was too high to operate in a stable manner. A clear difference of the performance with regards to different traffic mixes could not be observed.



**Figure 4 – Transition of Control percentage for different scenarios**

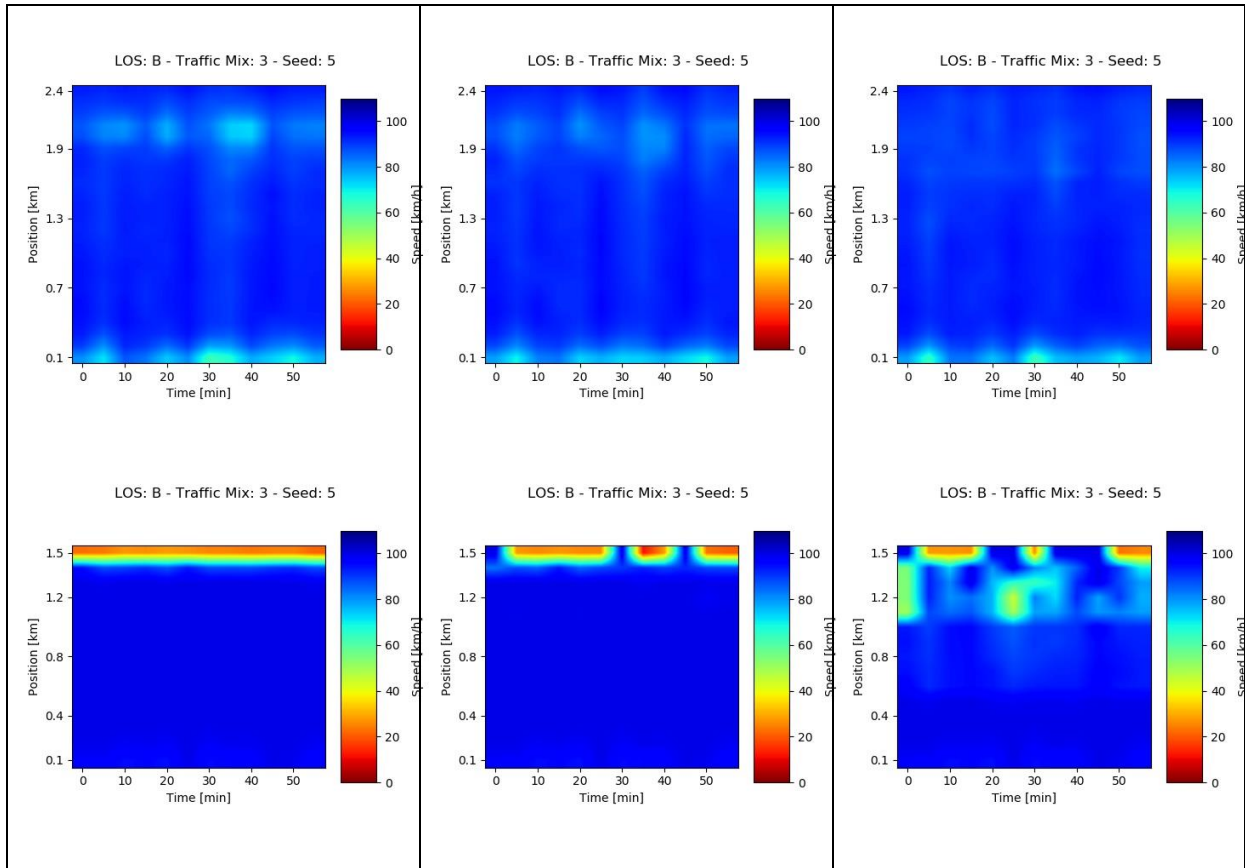
When looking at traffic efficiency, throughput, average number of stops, average network speed and average CO<sub>2</sub> emissions are the most interesting parameters. For throughput, no significant difference could be observed, which means that the shockwaves always resolved before reaching the start of the simulation network. The results of the stops and the average speed are shown in Figure 5:





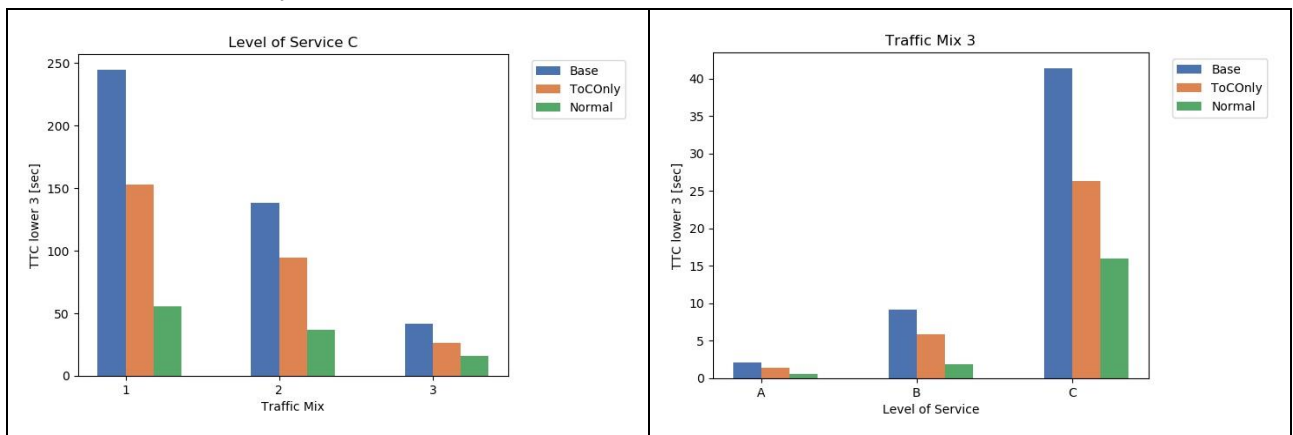
**Figure 5 – Average number of stops (top) network speed (left) and CO2 emissions (right) for different traffic intensities**

The stops are directly caused by human drivers not succeeding in merging into the main road. At LOS A, the stops can be almost completely eliminated from 0.14 to 0.02, which is also in line with the previously observed reduction in ToCs. With higher traffic volume it gets increasingly more difficult to find a gap, ToC percentage increases and therefore also the number of stops. The system still gives a benefit, but relatively speaking many stops are still made. This also propagates into the average speed that is reduced and the average CO<sub>2</sub> emissions which decrease. On the other hand, the CO<sub>2</sub> reduction is most significant for LOS C. When plotting the average speed in a time-space diagram, it is clearly visible that there are fewer speed reductions when more services of the merging assistant are switched on. This is shown in Figure 6.



**Figure 6 – Time space diagram of vehicle speed at main road (upper row) and onramp (lower row) for baseline (left column), ToC-only (middle column) and speed advice (right column)**

The last area of interest are the safety measures, for which the number of seconds that the time to collision for a vehicle was lower than 3 seconds was used as a safety indicator. This is the only indicator that shows a clear improvement when more C(A)V are present in the traffic mix. Figure 7 shows the results. Lower values indicate less risk and are therefore preferred. Clearly, the risk is more than halved with the system turned on.



**Figure 7 – Total time that a vehicle had a Time To Collision (TTC) lower than 3 seconds for LOS C with different traffic mixes (left) and for traffic mix 3 with different LOS (right).**

## **Conclusion and further research**

The paper presented a motorway merging assistant for automated vehicles capable of handling situations from 0% penetration of C(A)V to 100%. The main objective was to reduce the number of required ToCs for CAVs by giving speed advice. This was reduced by up to 92% when compared to the baseline. It was also clear that infrastructure sensors play a vital role in building up a model with sufficiently accurate information to give effective advice.

The objectives to increase traffic efficiency and safety were also achieved with very promising improvements. The effects of the ToC reduction also had a positive impact on traffic efficiency reducing the number of stops by up to 87% and a CO<sub>2</sub> reduction of up to 7.3%. Safety was also significantly improved with the number of increased risk situations with time to collision below 3 seconds more than halved.

On the other hand, there is clearly room for improvement with higher traffic volume. In part this was due to the complexity of modelling merging behaviour that can still be further refined. Additionally, new measures can be added to the system that were already demonstrated in literature that require C(A)V on the main road. These are cooperative speed and lane advice for gap creation. They will cause a minor disruption, but not as much as a human driver stopping or cutting in. Lastly, the onramp speed advice strategy can be combined with a ramp meter to increase the search space for finding a gap.

## **Acknowledgement**

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