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Enhanced Traffic Management Procedures of Connected and Autonomous Vehicles in Transition Areas

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Abstract

In light of the increasing trend towards vehicle connectivity and automation, 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. These are termed ‘Transition Areas’. Without proper traffic management, such areas may lead to vehicles issuing take-over requests (TORs), which in turn can trigger transitions of control (ToCs), or even minimum-risk manoeuvres (MRMs). In this respect, the TransAID Horizon 2020 project develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of automated, connected, and conventional vehicles, with the goal of avoiding ToCs and MRMs, or at least postponing/accommodating them. Our baseline simulations confirmed that, e.g., a coordinated distribution of takeover events can prevent drops in traffic efficiency, which in turn leads to a more performant, safer, and cleaner traffic system, when taking the capabilities of connected and autonomous vehicles into account.

Keywords: Traffic management; connected and autonomous vehicles (CAVs); V2X; transition areas

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1.1.1. Nomenclature

ADS	Automated driving systems
(C)AV	(Connected and/or) autonomous vehicle
MCM	Minimum-risk manoeuvre
NAD	No automated driving
ODD	Operational design domain
OEM	Original equipment manufacturer
OREM	Operational road environment model
SAE	Society of Automotive Engineers
TA	Transition area
ToC	Transition of control
TOR	Take-over request
TransAID	Transition areas for infrastructure-assisted driving
V2X	Vehicle-to-anything

2. Introduction

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'.

Without proper traffic management, such areas may lead to vehicles issuing take-over requests (TORs) to their drivers, which in turn can trigger transitions of control (ToCs) towards these drivers, or even minimum-risk manoeuvres (MRMs) by the vehicles themselves. In this respect, the TransAID Horizon 2020 project ('Transition Areas for Infrastructure-Assisted Driving') develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of automated, connected, and conventional vehicles, with the goal of avoiding ToCs and MRMs, or at least postponing/accommodating them.

3. Outline of the traffic management framework

3.1. Techniques for traffic management

In first instance, TransAID compiled an outline of the state-of-the-art of traffic management, putting the focus first on general approaches, including coordinated network-wide traffic management, using KPIs, layered architectures spanning the range from top-down regulation over self-organisation to full bottom-up regulation, and even Traffic Management-as-a-Service. We also looked at the trend towards more cooperative systems which is well-suited for enhanced traffic management, making the systems smarter by targeting (cooperative/connected) vehicles individually. Moreover, we looked at the expected impacts that machine learning techniques and artificial intelligence in general would have on traffic management. Note however that as of yet there do not exist (readily available) implementations of these more advanced traffic management schemes. Finally, we also reviewed the existing procedures and protocols for traffic management, how to adhere to standards and policies (on the strategical, tactical, and operational/technical levels), and to integrate these with existing road-side systems, explained the link between goals, policies, and strategies, considered the EC perspective via its ITS Directive, C-ITS platform, and SUMPs.

In itself, all these solutions are very fine and usable. However, there are no (readily available) integrated traffic management experiments or setups, taking higher degrees of vehicle automation into account. Nor do they allow the interplay between all the various solutions to lead to a better system performance. This is where TransAID makes the difference by creating a traffic management framework. Fleet managers of connected and/or autonomous vehicles (CAVs), as well as road authorities, both operate backend centres to manage their fleets and traffic networks, respectively. A more encompassing solution is needed to manage all these transition areas, as well as the different stakeholders.

3.2. TransAID in the role of an intermediary service provider

Automated vehicles of different makes with different levels of automation will each be designed to operate in a particular domain. Such a domain is characterised by static and dynamic attributes which range from road type and layout to traffic conditions, weather and many attributes in between. In general, we call these domains 'operational design domains' (ODD), which are defined by Czarnecki (2018) as the operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics. An ODD may put limitations on (i) the road environment, (ii) the behaviour of the automated driving systems (ADS)-equipped subject vehicle, and (iii) the state of the vehicle. Furthermore, an operational road environment model (OREM) is a representation of the relevant assumptions about the road environment in which an ADS will operate the ADS-equipped vehicle (e.g., a two-lane rural road). An ODD of an ADS implies a set of operational environments in which the ADS can operate the ADS-equipped vehicle. These environments can be specified using a set of OREMs, which can be in- or out-of-scope of the ODD.

When the ODD of an AV ends, it will handover the control of the vehicle to the human driver or in case the driver does not respond, initiate an MRM. The location of such an event is referred to as the TA. However, due to the stochastic nature of traffic (take the occurrence and impacts of incidents for example) and the diversity of automated vehicle makes and their capabilities, it is impossible to perfectly predict where, when, and why the ODD ends and consequently TAs are located. Nonetheless, the existence of TAs affects both AV-fleet managers and road authorities due to reduced performance of the vehicle and the traffic network respectively. Here, TransAID develops infrastructure support measures for situations which normally would imply the end of the ODD. However, as part of these support measures, AVs receive additional information and/or guidance needed to enable them to proceed in automation mode.

AV-fleet managers and road authorities both operate backend centres to manage their fleets and traffic networks, respectively. To effectively and systematically manage TAs on a large scale and for multiple AV fleets and multiple road authorities, we propose a trusted third party (and where possible mandated) intermediary service. It will then act as the single-point-of-contact for road authorities and traffic participants (or indirectly, via their OEMs). Based on status and disengagement information from AV fleet managers and traffic management plans from road authorities, this intermediary service acts as a delegated traffic manager who digitally implements the TransAID infrastructure support measures. With support of the right tools, an operator continuously monitors in real-time the traffic system and disengagement reports, based on triggers and scenarios, identifies TAs, and finally selects the appropriate measure. An advantage of this service is that measures taken by AV-fleet managers and road authorities can be coordinated and harmonised across multiple AV fleets and geographical areas (managed by different road authorities). Moreover, smaller and/or rural road authorities, which may not have backend centres or not a suitable operational overview of the road and traffic flow dynamics, can benefit from an intermediary service that can perform this task for them. The concept of the intermediary service approach adopted within TransAID's traffic management scheme is depicted in Figure 1.

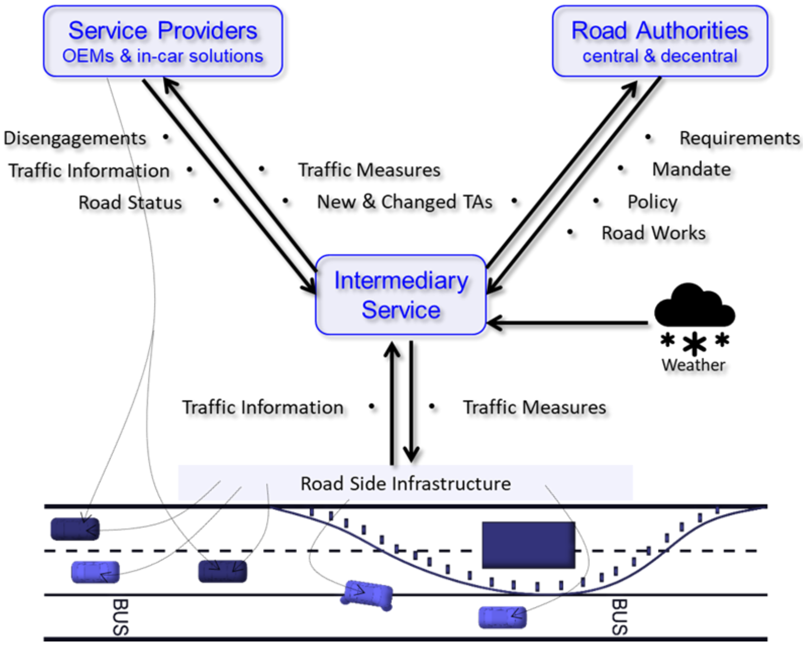


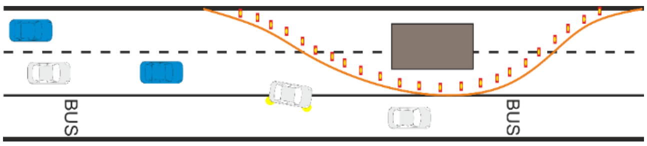
Figure 1: Schematic overview of TransAID's intermediary service approach.

4. TransAID's services and use cases

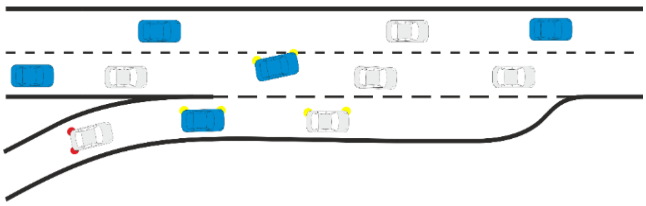
4.1. General overview

Within TransAID we defined five different use cases where disruptions of traffic flow are expected to be most severe as a result of transition between automation levels. The initially selected use cases were:

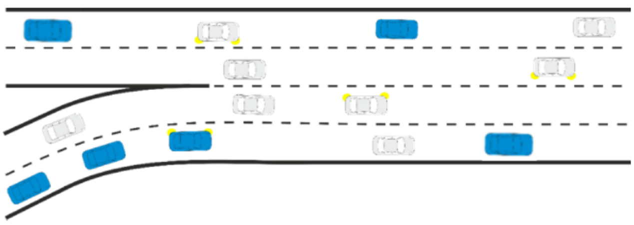
- Service 1 (Use case 1.1): Prevent ToC/MRM by providing vehicle path information



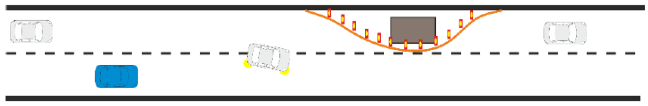
- Service 2 (Use case 2.1): Prevent ToC/MRM by providing speed, headway and/or lane advice



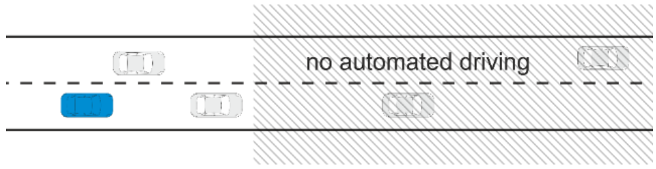
- Service 3 (Use case 3.1): Prevent ToC/MRM by traffic separation



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



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



In addition, we elaborated all use cases with general descriptions, timelines, road networks, and requirements on the vehicle capabilities, vehicle numbers, and traffic compositions. For each of these use cases, we listed when (i.e. for which Level of Service and vehicle mix), where (what is the spatial extent of the transition area, and at which location should the system inform vehicles/drivers?), and how (what specific traffic management measures should be taken?) traffic management measures should be applied.

4.2. Used traffic conditions and vehicle mixes

The 'right' traffic management measures are dependent on traffic conditions and the vehicle mix. The following Tables 1, 2, and 3 give an overview of their values:

- Definition of the levels of service (LOS) A through C (HCM, 2010)
- Distribution of passenger vehicles versus LGV and HGV
- Overview of the different vehicle types, aggregated into classes of actors
- Artificial vehicle mixes for baseline simulations

Table 1: 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 2: Classification of actors (vehicle types).

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

Table 3: 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%	-	-

4.3. Simulation and analysis methodology

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

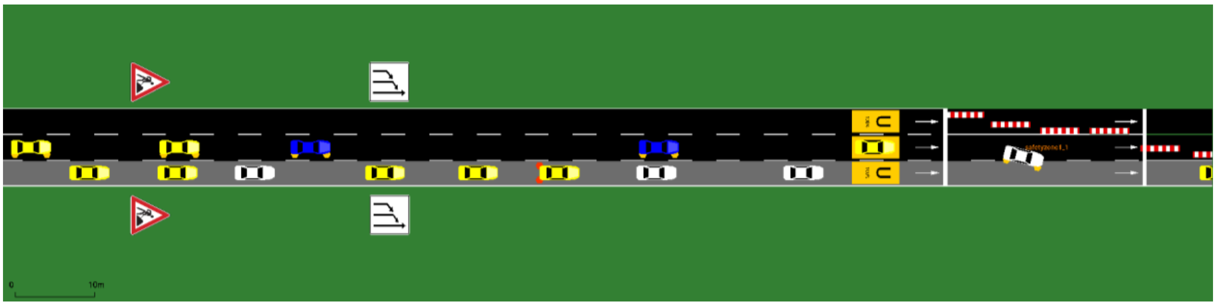


Figure 2: Detail view of the merging area in SUMO for scenario 1. The grey lane is usually reserved for public transport but opened temporarily to provide a possibility to pass the construction works stretching over the two main lanes. Vehicle colours indicate the vehicle type (yellow for legacy vehicles, blue for CAVs, and white for CVs).

5. Example Service 5 / Use case 5.1

5.1. Introduction

As an example, we look at Service 5 / Use case 5.1, i.e. Distribute ToC/MRM by scheduling ToCs. Here, 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 3).

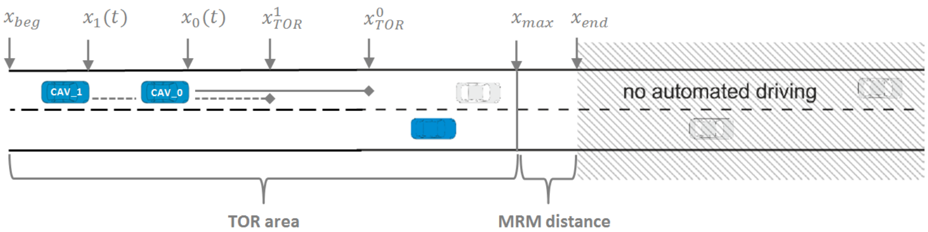


Figure 3: Schematic distribution area for TORs within a transition area.

5.2. Traffic management setup

In Figure 4 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.

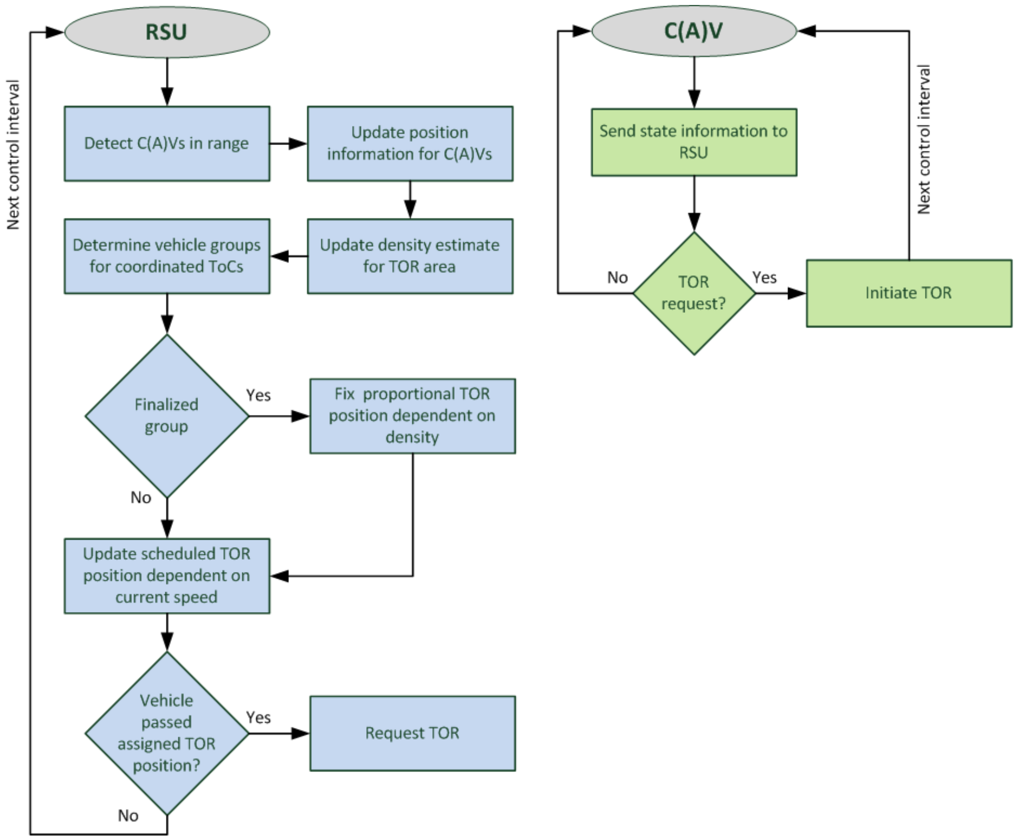


Figure 4: Traffic management block diagram for use case 5.1.

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. It takes in-group coordination into account, and aims to prevent the compounding of braking efforts. Generally speaking, the timeline of events for Service 5 is given as follows:

```
TIMELINE OF SERVICE 5
Collect information about the area
Collect information about traffic stream
Calculate traffic stream composition
Define Service Area
Alert vehicles about the no AD-zone
Create virtual queue for CAVs
Decide the places for executing ToC
For each CAV entering in the area do
  Determine CAV rank in the virtual queue
  Add CAV to virtual queue
  Select the next CAVs to execute ToC
  For each selected CAV do
    Disseminate time and place of the ToC
    Instruct nearby CAVs with safety measures
    CAV executes ToC
    Nearby CAVs execute safety measures
  End for
  Check for CAVs that exit the area
  Remove those CAVs from the virtual queue
End for
```

5.3. Simulation results

Within TransAID, we simulate the different use cases first as a baseline using the earlier mentioned parameters, and then with the activation of the chosen traffic management service. For Service 5, we can see for example how, given the network, activation of the traffic management system leads to a higher average network speed compared to the baseline for Level of Service C, as shown in the graphs in Figure 5.

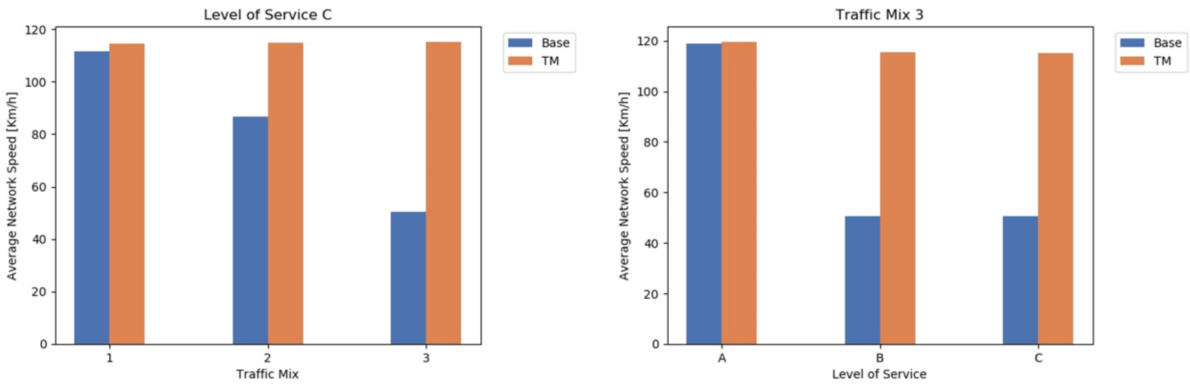


Figure 5: Average network speeds for use case 5.1 (motorway network) simulation experiments (varying the LOS and vehicle mixes). Different bar colours correspond to baseline and traffic management simulations.

Figure 6 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 the Figure).

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 the Figure), 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 the Figure).

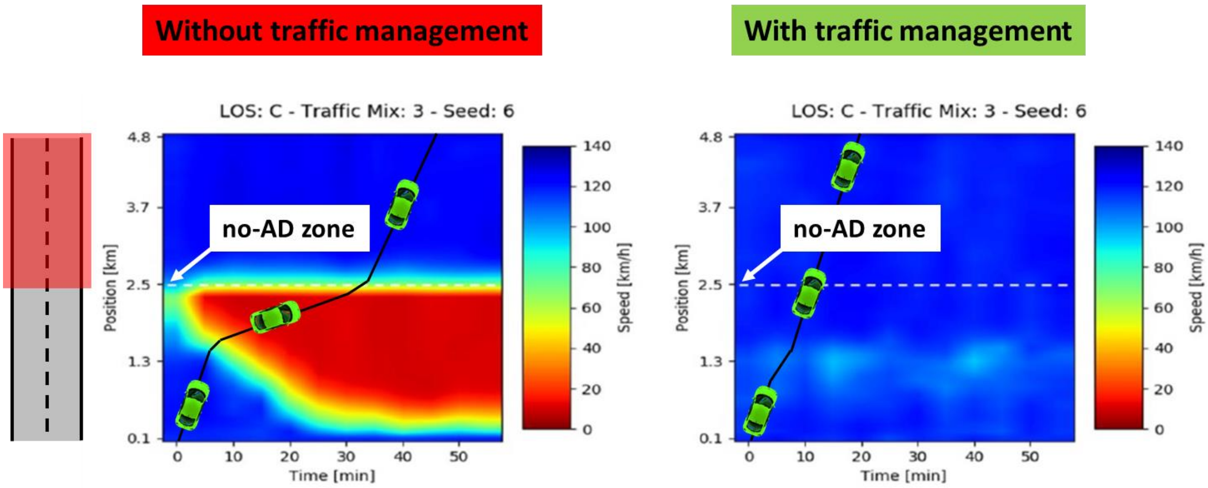


Figure 6: Example tempo-spatial diagrams for measured speeds for use case 5.1 (LOS C, vehicle mix 3, seed 6). The left diagram corresponds to the baseline and the right one to the applied traffic management Service 5 simulations. The white dashed line marks the entry position of the NAD zone.

6. Main results

6.1. Results for all the use cases

A complete overview of the results can be found in (TransAID D4.2, 2019). In the following paragraphs, we summarise the main results:

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

- The second service was applied to a motorway merge area where AVs are given speed advice to merge onto the motorway (see also Blokpoel, 2019). The service slightly increased average network speed and slightly decreased CO_2 emissions, especially in case of higher demand (LOS C). The impact on safety was more pronounced with a reduction of critical events around 75%.

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

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

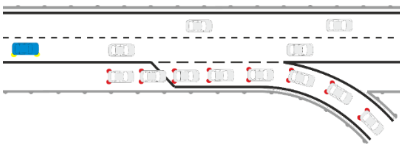
- Finally, a no automated driving zone was simulated along the downstream part of a two-lane motorway for the fifth service. The zone can represent different situations (e.g., road works, geofences, weather, accidents, …) that prevent AVs from staying in automated driving mode. It is assumed that AVs increase their headway before handing over control to the driver. When this happens in a concentrated fashion just before the no-AD zone, traffic flow is impacted. We therefore distribute these handovers in time and space upstream of the zone. It was found that this service greatly smoothens out the disturbances caused by the handovers and improves traffic efficiency, as also elaborated upon Section 0.

6.2. Next steps and new use cases

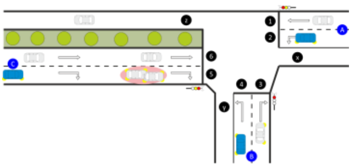
The infrastructure-assisted management solutions are developed and tested in two iterations, each taking half of the project total duration. During the first iteration, the focus lay on studying aspects of transition of control and transition areas through basic scenarios. To this end, we developed and adopted realistic models for automated driving and ToC. Using the basic scenarios, we ran many simulations and focused in detail on the relatively new aspects of ToC, transition areas and measures mitigating negative effects of TAs. The goal of the first iteration was to gain experience with all aspects relevant to TAs and the mitigating measures. During the second iteration which has just started, all of the previous experience is used to improve/extend the measures while at the same time increasing the complexity/realism of the scenarios and/or selecting different (more complex) scenarios. Moreover, it is used to enhance AV and driver models to accurately capture the effects of ToCs/MRMs on safety, traffic efficiency, and the environment.

To this end, we will also focus on the following new scenarios: Scenario 1.3 (Queue spillback at exit ramp), Scenario 2.3 (Intersection handling due to incident), and Scenario 4.1 + Service 5 (4.1-5) (Distributed safe spots along an urban corridor).

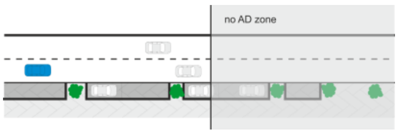
Scenario 1.3



Scenario 2.3



Scenario 4.1 + Service 5



These new scenarios partly focus on new situations and others combine multiple measures (services) into one scenario. It is expected the hierarchical approach of applying multiple services (i.e. speed and lane advice, safe spot reservation, and ToC requests) in parallel or sequential will result in improved mitigation of the negative impact of transition areas. In addition, we will research ideas to improve on vehicle modelling (i.e. lane change behaviour and ToC/MRM behaviour). Moreover, enhanced cooperative manoeuvring (merging) will be also investigated. Furthermore, to focus on more realistic scenarios, each scenario will be extended with opposite traffic to create realistic communication traffic and support the evaluation of possible congestion of the communication channels. Also, other types of vehicles will be used to create a more realistic traffic mix (i.e. adding light good vehicles and heavy good vehicles), aside from the already proposed mixes of vehicles encompassing different communication and automation capabilities.

7. Conclusions

It is clear that advanced traffic management procedures lead to a more performant, safer, and cleaner traffic system, when taking the capabilities of connected and autonomous vehicles into account. As an example of a traffic management service, our baseline simulations confirmed 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.

Acknowledgements

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References

Blokpoel, R. et al. (2019). Motorway merging assistant for automated vehicles, in proceedings of the 13th ITS European Congress, Brainport, The Netherlands, 3—6 June 2019

Czarnecki K. (2018). Operational Design Domain for Automated Driving Systems: Taxonomy of Basic Terms, Waterloo Intelligent Systems Engineering (WISE) Lab, University of Waterloo, Canada

TransAID (2018-2019). Deliverable D4.1: Overview of Existing and Enhanced Traffic Management Procedures / Deliverable D4.2: Preliminary simulation and assessment of enhanced TM measures

Maerivoet S. et al. (2019). Enhanced Traffic Management Procedures in Transition Areas, in proceedings of the 13th ITS European Congress, paper number ITS-TP1971, Brainport, The Netherlands, 3—6 June 2019

National Research Council (U.S.) (Ed.). (2010). Highway Capacity Manual. Washington, D.C.: Transportation Research Board, National Research Council