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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. 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.

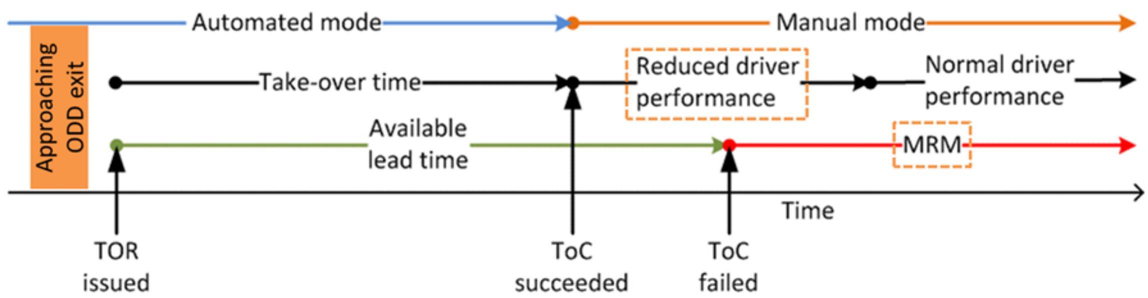


Figure 1: Chronological timeline of sequence of TOR ⇔ ToC ⇔ MRM events.

2. A vehicle's operational design domain

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. An ODD that ends leads to a TOR, which in turn can cause an MRM due to a failed ToC. TransAID's main goal is to avoid the MRM, and preferably the TOR, by optimally providing advice to vehicles. Even if a planned ToR is followed by a controlled ToC (as it is in the nature of L3 automation), it would nevertheless lead to a suboptimal traffic situation. Hence, lowering the risk of failed ToCs by providing appropriate traffic management increases both traffic efficiency safety.

3. TransAID in the role of an intermediary service provider

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 car manufacturers, i.e. the 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.

4. TransAID's services and use case

4.1. General overview

Within TransAID we defined five services which would help to alleviate disruptions of traffic flow that expected to be most severe as a result of transition between automation levels:

- Service 1: Prevent ToC/MRM by providing vehicle path information
- Service 2: Prevent ToC/MRM by providing speed, headway and/or lane advice
- Service 3: Prevent ToC/MRM by traffic separation
- Service 4: Manage MRM by guidance to safe spot
- Service 5: Distribute ToC/MRM by scheduling ToCs

We then selected and elaborated ten different use cases that give specific, realistic situations in which the previously mentioned services can be used; they are the following ones, and shown in Figure 2.

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

These ten use cases are all individually modelled, simulated, and discussed in detail in TransAID's Deliverables D4.1 and D4.2 (Maerivoet S. et al., 2019). 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.

5. Simulation and analysis methodology

5.1. Main simulation overview

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 CO2 emissions as calculated by SUMO's PHEMlight emissions model).

5.2. Example Service 1 / Use case 1.3 (queue spillback at motorway exit ramp)

As an example, we look at Service 1 / Use case 1.3, i.e. queue spillback at motorway exit ramp. Figure 2, number 3, depicts a CAV (blue) and LVs (light-coloured) approach an exit on a motorway. There is a queue on the exit lane that spills back onto the motorway. We consider a queue to spill back on the motorway as soon as there is not enough space on the exit lane to decelerate comfortably (drivers will start decelerating upstream of the exit lane).

Vehicles are not allowed to queue on the emergency lane, but queuing on right-most lane of the motorway will cause (a) a safety risk due to the large speed differences between the queuing vehicles and the regular motorway traffic, and (b) a capacity drop for all traffic (including vehicles that do not wish to use the exit). In the baseline of this scenario vehicles queue on the main road and the speed limit remains unchanged (drivers have to decide themselves to slow down when noticing the queue). This is a well-known situation which leads to the so-called 'blocking back' effect (that, amongst others, traffic flow models, such as SUMO, must be able to reproduce in order to exhibit realistic dynamics and to be used as a proxy for a simulation of reality). It is observed on, e.g., the E19 motorway near Antwerp in Belgium.

In the traffic management case, the road-side infrastructure (RSI) will monitor traffic operations along the motorway, the off-ramp, and exit lane, and when a queue spillback is detected, a section of the emergency lane will be opened. As such, vehicles that wish to exit the motorway will be able to decelerate and queue safely without interfering with the regular motorway traffic. The length of the section of the emergency lane that is opened for traffic will be determined dynamically by the RSI. The speed limit on the main road will also be reduced to increase safety. The reduction of speed limit will be gradual: first the upstream end of the queue is detected. Then we calculate the distance required to decelerate comfortable. Next, we find the first encountered upstream VMS from this point where deceleration would start. At this point we apply a speed limit of 50 km/h. The subsequent upstream VMSs will then in sequence display 70 km/h and 90 km/h (the distance of 250 m between VMSs is sufficient for decelarating comfortably to the next speed limit). This speed limit is reduced to the same speed for all lanes. The speed limit and the status of the emergency lane (whether or not it is open for queuing) is communicated using both VMSs and V2X (to CVs and CAVs). Because the same restrictions have to apply to all vehicles, the resolution of the VMS's is also used for communication with the C(A)Vs. In the use case, a series of VMS-portals is located at a 250 m interval upstream of the exit lane.

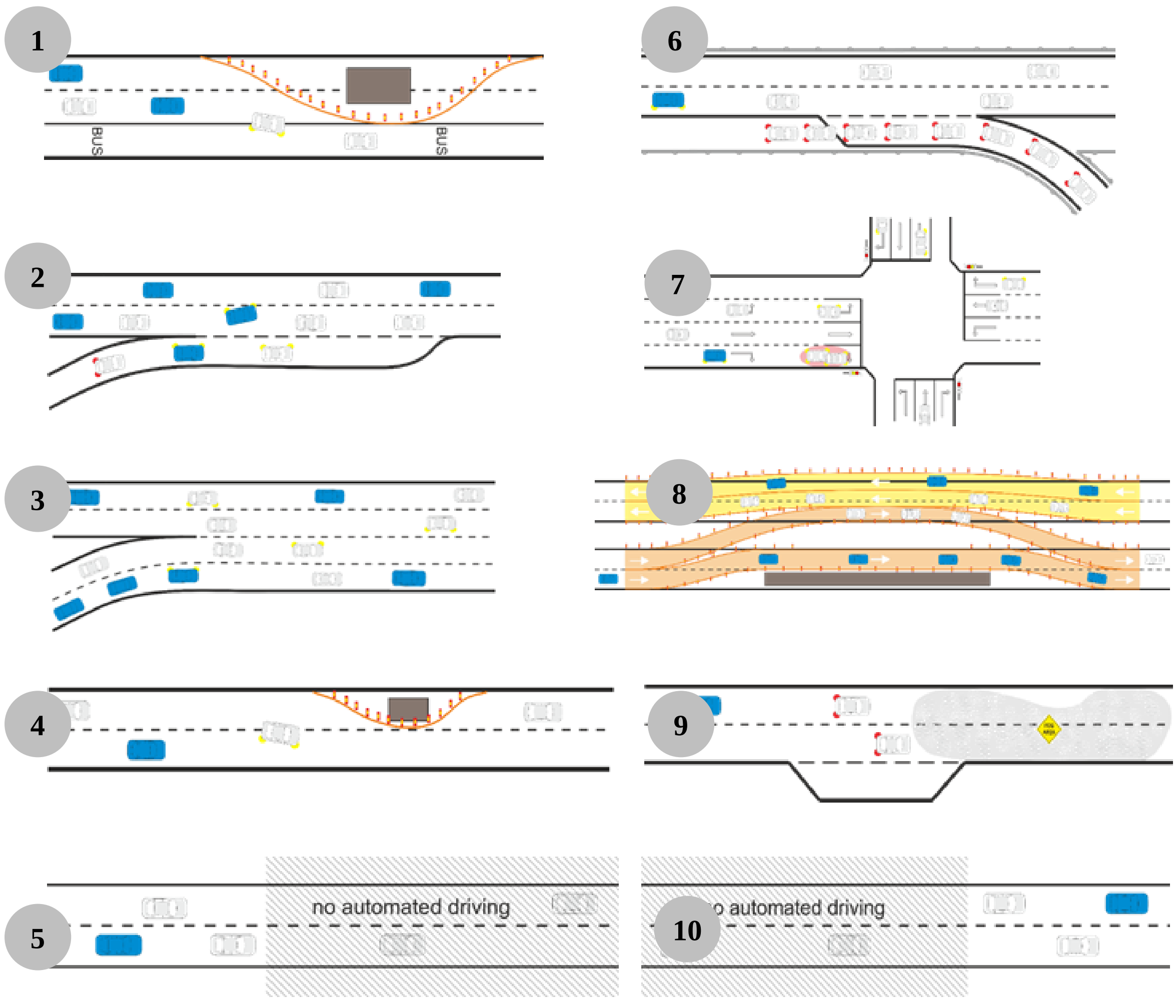
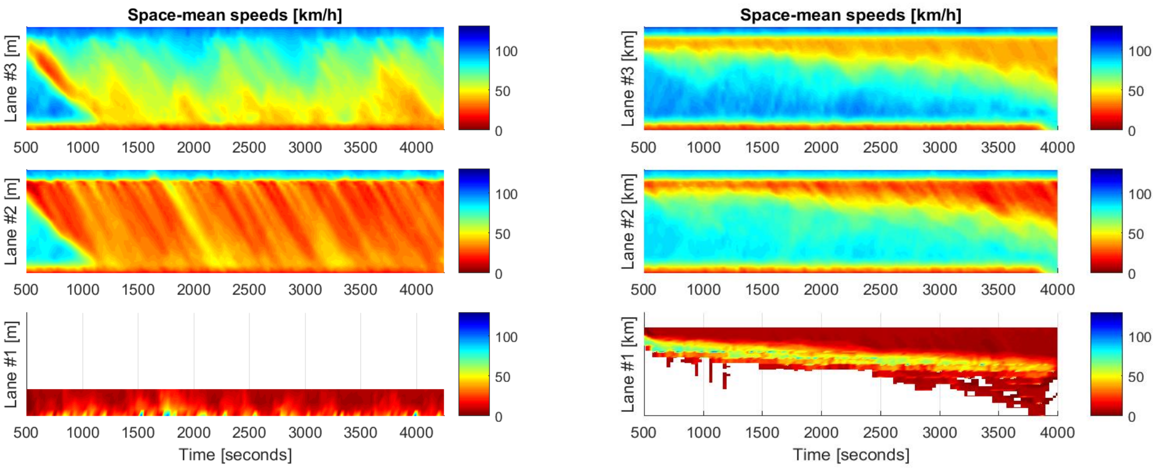


Figure 2: Overview of the selected use cases that were studied in TransAID.

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.

The time-space diagrams in the left column of Figure 3 show how in the baseline scenario the congestion steadily grows, filling the entire motorway. Traffic on the motorway will slow down because of the dynamic speed limit (lane 3) and/or because of vehicles that are trying to merge in the queue for the exit (mostly limited to lane 2). When traffic management is activated however (right column), we can see how congestion is significantly reduced on all lanes in the latter one. This has a beneficial effect on all indicators. The average travel time decreases, despite the speed limits applied in the traffic management scenario. Further experiments showed that the throughput increases strongly between LOS B and LOS C in the traffic management scenario. The average number of safety-critical events increases with the LOS and with the share of AVs in the vehicle mix, but it is still significantly reduced compare to the baseline.

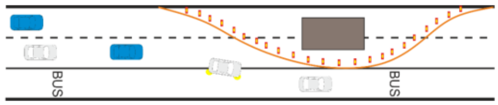
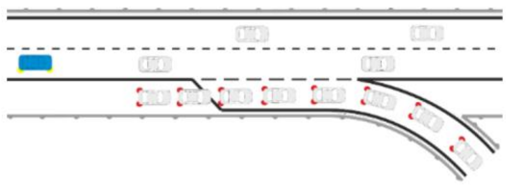
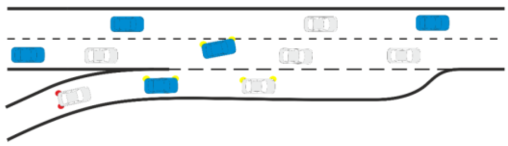
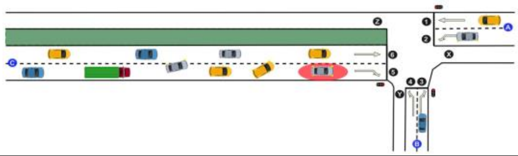
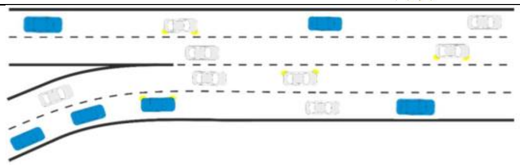
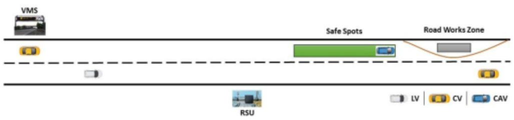
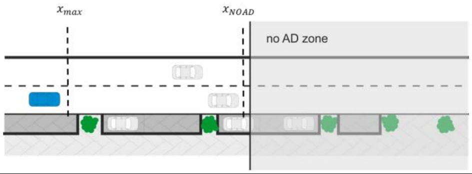
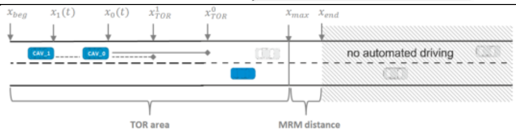


Baseline scenario (LOS D, Vehicle Mix 1) *Traffic management scenario (LOS D, Vehicle Mix 1)*

Figure 3: Comparison of the aggregated time-space diagrams per lane for use case 1.3 simulation experiments for LOS D and vehicle mix 1 (each time, top: left lane, middle: right lane, bottom: emergency lane/off-ramp), in the baseline (left column) and traffic management.

6. 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 evidenced by the example use case discussed in this paper. A complete overview of the results can be found in TransAID's deliverable D4.2. In addition, to make matters more realistic, all use cases were implemented with enhanced cooperative manoeuvring (merging) in the simulations, as well as realistic V2X communications (bandwidth allocation and channel congestion using the ns-3 simulator). The experiments were also carried out with real CAVs, in part, in real-world conditions on the Braunschweig testing track. All results can be found at the website www.transaid.eu. The following table presents a summary with the results for each use case, emphasising its impact on traffic flows (efficiency), traffic safety, and vehicle emissions.

Use case	Efficiency	Safety	Emissions	Comments	Schematic overview of the use case
1.1	~	+	~	Safety critical events reduced by 45% to 70%, depending on LOS and traffic mix.	
1.3	+	+	+	For higher traffic intensities and a larger share of AVs, the effects diminish but are still positive. When the queue grows too large and vehicles stop on the main road, safety and efficiency are affected strongly.	
2.1 (1st)	~	+	~	Large safety improvement and marginal improvements for both efficiency and emissions.	
2.1 (2nd)	-	+	-	This use-case identified a clear trade-off between safety and throughput, depending on merging settings.	
2.3	+	+	+	As long as traffic remains stable all effects are positive, performance becomes worse on all KPIs when breakdown occurs, but still less severe compared to the baseline.	
3.1	~	-	~	Safety is severely affected due to increased number of cut-in lane-changes. Increased CAV share and cooperative manoeuvring seems promising to improve the results.	
4.2 (1st)	~ (U) ~ (M)	+ (U) + (M)	+ (U) + (M)	Large safety improvements. Safety effects are smaller for a higher share of AVs and LOS.	
4.2 (2nd)	~ (U) + (M)	+ (U) + (M)	+ (U) + (M)	Increased share of AVs and higher LOS dimish the safety effects, as expected.	
4.1 + 5.1	+	+	+	Large improvements on all measures. Higher traffic intensities result in relatively larger improvements.	
5.1	+	+	+	Large improvements on all aspects due to the smoothening of disturbances.	

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