Paper number TP2170

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 simulations confirmed that proper traffic management, taking the traffic mix into account, 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); transition areas

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*' (TAs).

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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, as shown in Figure 1.

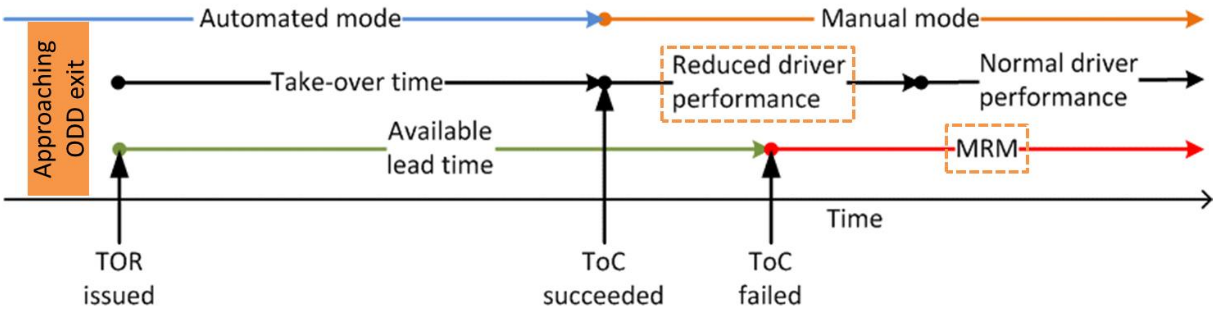


Figure 1: Chronological timeline of sequence of TOR→ToC→MRM events.

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.

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 [4] 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. Outline of the traffic management framework

2.1 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 are well-suited for enhanced traffic management, making the systems smarter by targeting (cooperative/connected) vehicles individually. More and more countries are finding the way to enabling C-ITS on their major roads, albeit mostly in pilot trials as explained by van Waes and van der Vliet [8]. Using cooperative adaptive cruise control and a state-feedback mechanism of model predictive control, a traffic management system can even – in real-time – direct vehicles towards desired behaviour, i.e. keeping certain distances as described by Wang et al. [9]. Coupling roadside infrastructure to the vehicles as the next level/generation of traffic management approaches ties in with the intelligent transportation systems, by exploiting the distributed nature of the system and by making use of coordination and cooperation between the various vehicles both among each other and the infrastructure as explained by Baskar [2]. However, an often overlooked issue is to what degree the existing infrastructure is suited for such vehicles, and what needs to change in case it is not, as explained by Johnson [5] and Akkermans et al. [6].

And let us also note the work done in the Traffic Management 2.0 Task Force, as reported by Tzanidaki and Pelfrene [12] has to be noted. The traditional situation presents several actors, i.e. road operators and service providers, both involved in a cycle of tasks going from measuring, over influencing traffic, to guiding and informing drivers. The vision set out in TM 2.0 is to enable vehicle integration with traffic management. Furthermore, our literature review also 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 and deploying a **traffic management framework**. Fleet managers of connected and/or autonomous vehicles ((C)AVs), 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.

2.2. 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 cases

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

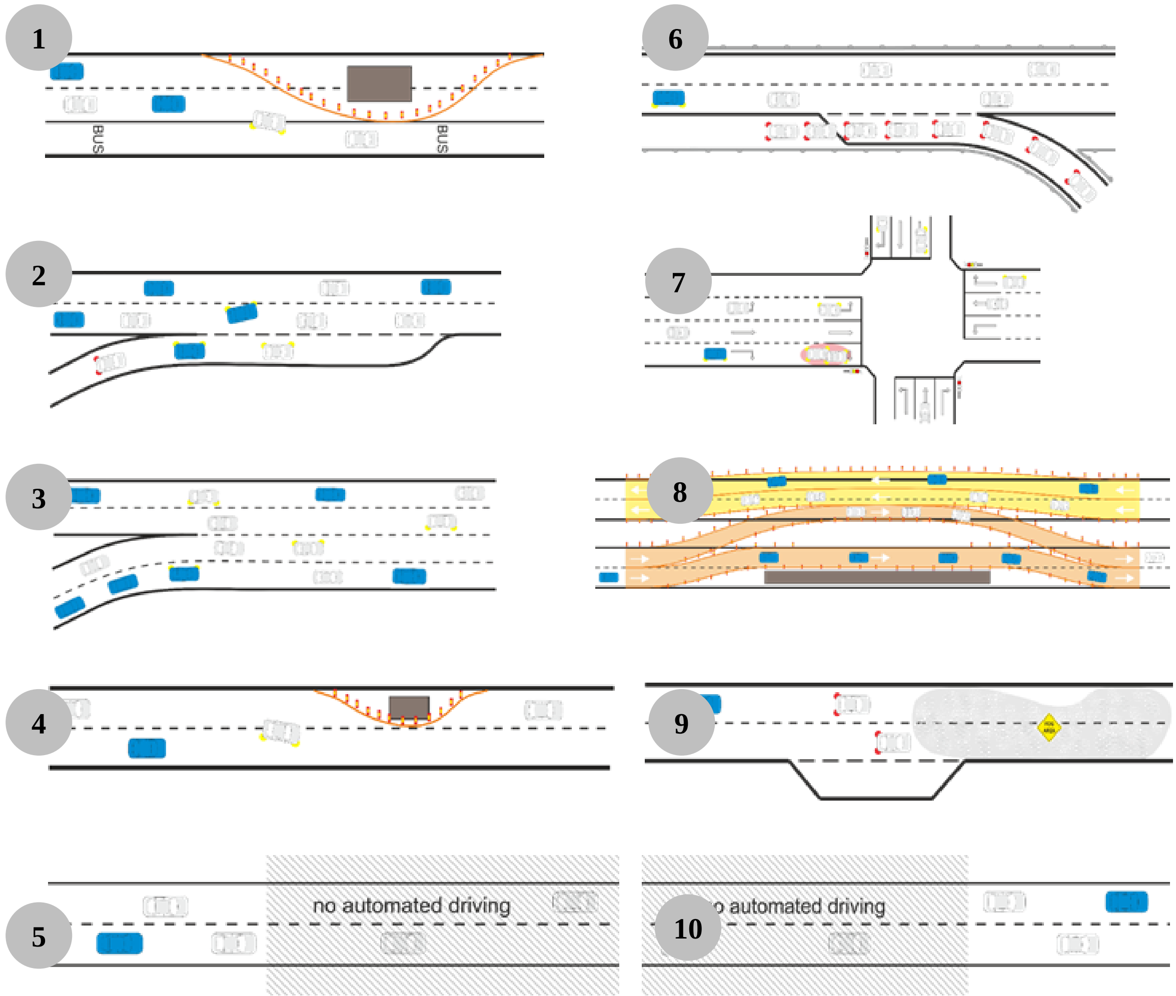


Figure 2: Overview of the selected use cases that were studied in TransAID.

These ten use cases are all individually modelled, simulated, and discussed in detail in TransAID's Deliverables D4.1 and D4.2 [11].

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. Tables 1, 2, 3, and 4 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	LOS D
Urban (50km/h) – 1500 veh/h/l	525	825	1155	1386
Rural (80 km/h) – 1900 veh/h/l	665	1045	1463	1756
Motorway (120 km/h) – 2100 veh/h/l	735	1155	1617	1940
Intensity / Capacity (IC) ratio	0.35	0.55	0.77	0.92

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.

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%	-	-

Table 4: Distribution of passenger vehicles, light and heavy goods vehicles.

Vehicle type	Share on urban roads	Share on motorways
Passenger vehicle	87%	77%
LGV	10%	10%
HGV	3%	13%

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 (see also Figure 3), 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).

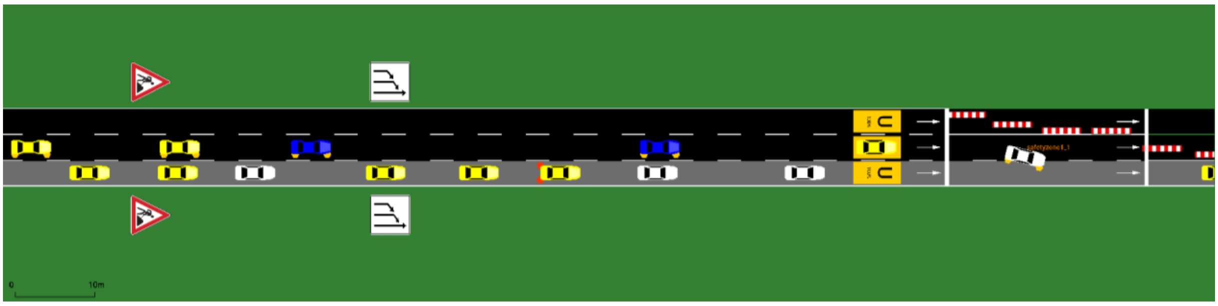


Figure 3: Detail view of the merging area in SUMO for scenario 1. The grey lane is usually reserved for public transport but opened temporarily to provide a possibility to pass the construction works stretching over the two main lanes. Vehicle colours indicate the vehicle type (yellow for legacy vehicles, blue for CAVs, and white for CVs).

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

5.1. Introduction

As an example, we look at Service 1 / Use case 1.3, i.e. queue spillback at motorway exit ramp. Figure 4 depicts a CAV (blue) and LVs (light-coloured) approach an exit on a motorway. There is a queue on the exit lane that spills back onto the motorway. We consider a queue to spill back on the motorway as soon as there is not enough space on the exit lane to decelerate comfortably (drivers will start decelerating upstream of the exit lane).

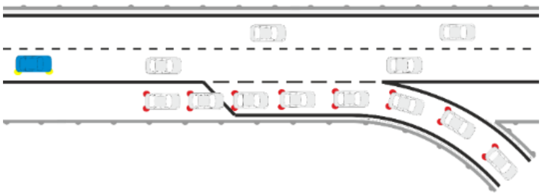


Figure 4: Detail view of the merging area in SUMO for scenario 1. The grey lane is the emergency lane, but opened temporarily to provide a possibility to house the upstream flowing queue. Colours indicate the vehicle type (white for legacy vehicles, blue for the CAV).

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.

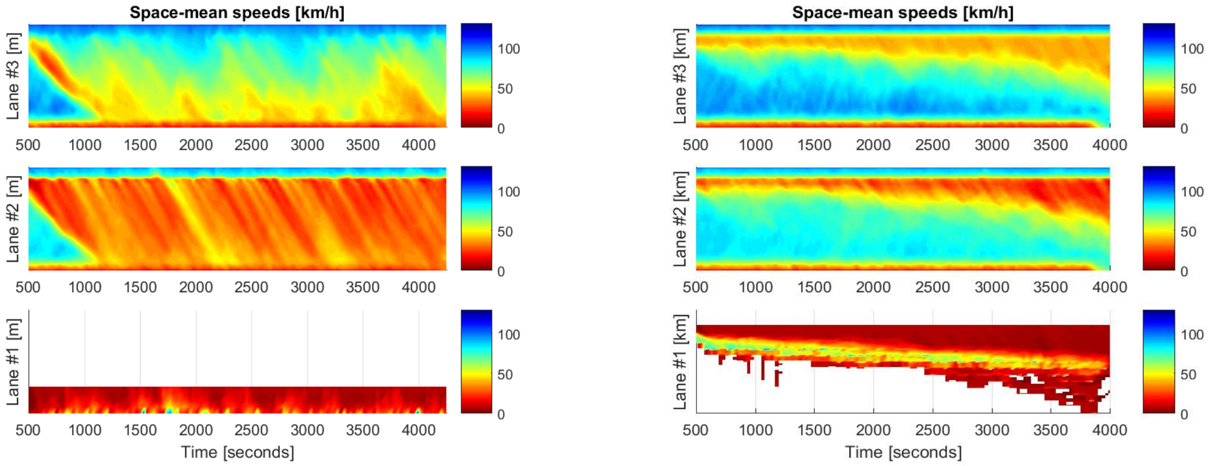
5.2. Traffic management setup

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.

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.



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

Figure 5: 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 (right column) scenarios.

The time-space diagrams in the left column of Figure 5 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.

6. Conclusions and next steps

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 [11]. The next step (with work being performed in 2020) will integrate enhanced cooperative manoeuvring (merging) in the simulations. Furthermore, to focus on more realistic scenarios, each scenario will be extended with realistic V2X communications (bandwidth allocation and channel congestion using the ns-3 simulator). The experiments will also be carried out with real CAVs, in part, in real-world conditions on the Braunschweig testing track, as well as demonstrations at conferences.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723390.

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