D4.1

Overview of Existing and Enhanced Traffic Management Procedures

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☐ RE: Restricted to a group specified by the consortium (including the Commission Services)

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1 Introduction

In the following sections we first give a concise overview of the TransAID project, followed by the purpose of this document, and finally present its structure.

1.1 About TransAID

As the introduction of automated vehicles becomes feasible, even in urban areas, it will be necessary to investigate their impacts on traffic safety and efficiency. This is particularly true during the early stages of market introduction, where automated vehicles of all SAE levels, connected vehicles (able to communicate via V2X) and conventional vehicles will share the same roads with varying penetration rates.

There will be areas and situations on the roads where high automation can be granted, and others where it is not allowed or not possible due to missing sensor inputs, high complexity situations, etc. Moving between those areas, there will be areas where many automated vehicles will change their level of automation. We refer to these areas as “Transition Areas”.

TransAID develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of automated, connected, and conventional vehicles, especially at Transition Areas. A hierarchical approach is followed where control actions are implemented at different layers including centralised traffic management, infrastructure, and vehicles.

First, simulations are performed to find optimal infrastructure-assisted management solutions to control connected, automated, and conventional vehicles at Transition Areas, taking into account traffic safety and efficiency metrics. Then, communication protocols for the cooperation between connected/automated vehicles and the road infrastructure are developed. Measures to detect and inform conventional vehicles are also addressed. The most promising solutions are then implemented as real world prototypes and demonstrated under real urban conditions. Finally, guidelines for advanced infrastructure-assisted driving are formulated. These guidelines also include a roadmap defining activities and needed upgrades of road infrastructure in the upcoming fifteen years in order to guarantee a smooth coexistence of conventional, connected, and automated vehicles.

1.2 Purpose of this document

This report describes the creation of the next generation of traffic management procedures and protocols that address the presence of autonomous vehicles, as to be deployed in TransAID. It serves to highlight the state-of-the-art of traffic management procedures, complementing this with methods to solve problems occurring at Transition Areas (as provided by WP2). The goal is to answer questions such as: what are the available traffic management options (and feasible extensions of these) for the presented set of use cases? How can traffic be optimally guided, e.g., through road sections with a lane closure? The available options are researched in terms of capabilities of and at (un)signalised intersections, various physical infrastructural characteristics, special road provisions for autonomous vehicles (dedicated lanes, zones, ...), et cetera. The revised version in M24 will update this deliverable by including the corresponding information for the second iteration.

1.3 Structure of this document

In this document we first outline the state-of-the-art of traffic management in section 2, thereby looking in turn at general approaches, including the coordination of CAVs, and conclude with the impact machine learning techniques and artificial intelligence in general have on traffic management. Continuing, section 3 elaborates on the traffic management procedures and protocols we will adopt within TransAID. For this, we first link traffic management to the concepts of goals, policies, and strategies. We then consider traffic management from an EC perspective with special emphasis on the C-ITS platform, ITS Action Plans, and Sustainable Urban Mobility Plans. The section then gives an explicit treatment of the outline of the traffic management framework to be used in TransAID. Here we position TransAID as an intermediary service provider, explain high- and low-level traffic management operations, and raise some discussion on the compliance of automated vehicles to traffic laws. The main part of the section then discusses the five selected services and use cases, each time highlighting when, where, and how traffic measures should be applied. The section concludes with some further approaches to integrated traffic management, paying special attention to the inclusion of CAVs in the loop. Before the document concludes, section 4 sketches several general communications requirements for traffic management systems, focusing on the types of messages.

> Note that with respect to some naming conventions on roadways, two different ‘standards’ exist for some of the encountered terminology, namely the American and the British standard. Examples are: the classical multi-lane high-speed road with on- and off-ramps, which is called a freeway or a super highway (American), or an arterial or motorway (British). A main road with intersections is called an urban highway (American) or a carriageway (British). In this work, we adopt the British standard. Finally, in contrast to Great Britain and Australia, we assume that for low-density traffic, everybody drives in the right instead of the left lane.

1.4 Glossary

ACC	Adaptive cruise control
ADAS	Advanced driver assistance systems
ADS	Automated driving system
AI	Artificial intelligence
ANN	Artificial neural network
AV	Automated vehicle
ATIS	Advanced traffic information systems
ATMS	Advanced traffic management systems
CaaS	Communication as a service
CAM	Cooperative awareness message
CAV	Cooperative automated vehicle
CC	Cruise control
CFVD	Cellular floating vehicle data
CPM	Collective perception message
CV	Cooperative vehicle
DENM	Decentralised environmental notification message
DTC	Dynamic traffic control
DTM	Dynamic traffic management
EC	European Commission
ESC/P	Electronic stability control/programme
FCD	Floating car data
FES	Fuzzy expert systems
FVD	Floating vehicle data
GIS	Geographical information systems

GLOSA	Green light optimised speed advisory
GPRS	General packet radio service
GPS	Global positioning system
GSM	Groupe Spécial Mobile
GSMC	Global system for mobile communications
HAV	Highly-automated vehicle
HMI	Human-machine interface
HOV	High-occupancy vehicle
I2I	Infrastructure-to-infrastructure
I2V	Infrastructure-to-vehicle
I2X	Infrastructure-to-anything
IaaS	Infrastructure as a service
IoT	Internet-of-things
ISA	Intelligent speed adaptation
ITS	Intelligent transportation systems
IVIM	Infrastructure to vehicle information message
(K)PI	(Key) performance indicator
LAM	Logical acknowledgement message
LDW	Lane departure warning
LOS	Level of service
LV	Legacy vehicle
MaaS	Mobility/Monitoring as a service
MAPEM	MAP (topology) extended message
MCM	Manoeuvre coordination message
MOE	Measure of effectiveness
MPC	Model predictive control

MRM	Minimum risk manoeuvre
NAD	No automated driving
NS2/3	Network Simulator 2/3
ODD	Operational design domain
OREM	Operational road environment model
PaaS	Platform as a service
PCE/U	Passenger car equivalent/unit
RFID	Radio-frequency identification
RL	Reinforcement learning
RM	Ramp metering
RSI	Road-side infrastructure
RSU	Road-side unit
SaaS	Software as a ¨service
SAE	Society of Automotive Engineers
SCOOT	Split cycle offset optimisation technique
SoMoClo	Social, mobile, and cloud
SSM	Surrogate safety measure
SUMO	Simulation of Urban Mobility
TA	Transition area
TC	Traction control
TCC	Traffic control centre
TCI	Task capability interface
TLC	Traffic light control
TM	Traffic management
TMaaS	Traffic management as a service
TMC	Traffic message channel

	Traffic management centre
ToC	Transition of control
TOR	Take over request
TransAID	Transition Areas for Infrastructure-Assisted Driving
UMTS	Universal Mobile Telecommunications System
VANET	Vehicular ad-hoc network
VITAL	Vehicle-actuated intelligent traffic signal control
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-anything
VMS	Variable message sign
VRU	Vulnerable road user
VSL	Variable speed limits
WSS	Wireless sensor networks
XaaS	Anything as a service

2 State-of-the-art traffic management

Autonomous vehicles will – by themselves – not solve traffic congestion. Even if all vehicles would become self-driving, then we would still need advanced control scenarios, both for intra- and intercity traffic. In this literature review, we present the state-of-the-art for traffic management procedures, giving attention to (i) general traffic management, (ii) coordinating CAVs, and (iii) artificial intelligence.

2.1 General traffic management

Even though area-wide traffic management has been around the block for a while, we notice a new trend in traffic management whereby new technology (V2X, autonomous vehicles, …) is introduced to systematically and automatically manage traffic according to observed and predicted states. The underlying principle is not to just look at single locations, but rather to use the entire network to distribute traffic more wisely and as such postpone or even prevent the formation of congestion. This 'coordinated network-wide traffic management' has been tested by Smits et al. (2016) in The Netherlands (Amsterdam), where they controlled a corridor section of the A10-West motorway with the goal of preventing (or at least postponing) a capacity drop at certain seed locations (on ramps, merging areas, …) that are prone to congestion formation. The control was done using the available classic infrastructure of ramp metering installations and variable message signs (VMS). The interesting innovation in this system is that it makes a distinction between jams that are fixed at a single location, and those that occur in waves. In essence, the management is done via a decision support system (DSS) that, based on the type of congestion occurring, makes decisions on how, where, and for how long to impose measures on the traffic flow. To do this, it takes into account the available buffer capacity in time and space (both upstream and downstream of the congestion zones). The next step in these experiments is to have better estimations of the congestion waves' locations, by means of floating car data that gives more insight into origin-destination relations.

Whereas the previous example of traffic management shows promise, it still lacks tackling the real challenge of network-wide management that goes beyond a single corridor. Such 'regional traffic management' implies a tighter coordination among different actors that are spatially separated as described by Birnie (2015). Historically, all local traffic centres adopt their own set of coordination rules to manage traffic and mitigate congestion, which are mostly executed automatically. Tactically streamlining these various rules with each other in a spatially broader setting (e.g., to coordinate road works, perform incident management, alternative routes, …) is then done via regional agreements and collaborating teams of operators and policy makers that exchange the necessary information.

Traffic management systems typically have a control loop that entails the road network, sensors, actuators, a control strategy, and human-machine interface (HMI). They are influenced by either control inputs (directly related to the present actuators) or disturbances (that cannot be manipulated but rather be measured, detected, or even predicted over a future time horizon), as described by Papageorgiou et al. (2003). Within urban contexts (and in some ramp metering cases), intersection control by means of traffic lights falls into the categories of isolated intersection control (using fixed-time and traffic-responsive strategies), fixed-time coordinated control, and coordinated traffic-responsive strategies (with the likes of the well-known SCOOT and model-based optimisation methods).

Erdmann et al. (2015) and Oertel et al. (2016) presented a new strategy using V2I-communication for an advanced intersection control algorithm combined with GLOSA (Green Light Optimised Speed Advisory). It was developed in the project VITAL (Vehicle-Actuated Intelligent Traffic Signal Control) and basically extends the planning horizon of the signal controller by using the exact position and speed of each vehicle and thus allows optimisation of an adapted signal plan. The switching times are then communicated back to these vehicles (although this option had to be neglected during a first validation field test due to currently low equipment-rates of vehicles with V2X).

In general, modern metropolitan traffic networks include both urban roads and motorways, using a broad range of control measures such as signal control, ramp metering, priority lanes for public transport and HOVs (high-occupancy vehicles), dynamic lane assignment, variable message signs, and route guidance. They can be further subdivided into link control (i.e. lane control, variable speed limits, congestion warnings, tidal flows, keep-lane instructions, …) and driver information and guidance systems (via V2V and V2I). The latter class is very noteworthy, as the (global) traffic management system typically has complete information on the network available, which is not always present for all the vehicles/drivers. Conveying such information to the road users, with the goal of allowing them to react to it and even adopt the given advice, can be done via different strategies. Examples of these are one-shot strategies (purely reactive and decentralised) and iterative strategies (going for user equilibrium or system optimal solutions).

A promising way of turning traffic management into a very lean service is by means of KPIs (key performance indicators), making the entire system performance-based. All processes are converted into a set of KPIs that are to be met. Everything that does not contribute to meeting the agreed upon performance is deemed unnecessary, leading to a more cost effective system. Of course, the first and foremost central question that needs to be answered then is "*What do we want to achieve with respect to the level of our ambitions?*" Once these ambitions are formulated into corresponding KPIs, we also define so-called 'norm values'. These are custom-tailored to the situation at hand, and allow checking whether or not a certain KPI meets its goals with respect to a(n ex-ante) base measurement as explained by Quirijns and Rakic (2017). As such, traffic management will move towards guarding societal constraints based on goals such as liveability, safety, and reachability, thus making more capacity available under both regular and special conditions (e.g. crises, calamities, …).

Improving traffic operations under specific conditions has also proven to be quite a challenge. Take for example work zones that have lane closures, a situation that associates well with TransAID. In these cases, vehicle queues in congested traffic may extend so far upstream that non-informed drivers are not prepared to stop in time (as they might not have been warned yet), hence greatly increasing the risk of rear-end collisions as explained by Pesti et al. (2007). Late merging strategies are one way of shortening traffic queues in this regard, albeit it should be made dynamic to account for low-volume/high-speed conditions. Regarding traffic safety, we can also extend the set of KPIs to a more macroscopic setting. These measures of effectiveness (MoE) are related to sudden stops, intensive breaking, forced lane changes (to avoid rear-end collisions), forced merges, last-minute lane changes, lane straddling and blocking to prevent such manoeuvers, speed variances, and the frequency of stop-and-go conditions.

Various frameworks and architectures for traffic management strategies exist, such as the PATH project (US), Dolphin (Japan), Auto21 Collaborative Driving System (CDS), Cooperative Vehicle-Infrastructure Systems (CVIS) (EU), SafeSpot (EU FP6), and PReVENT (EU), taken from the overview by Baskar et al. (2011). All these frameworks share more or less the same methodology, whereby hierarchical control is implemented via a layered architecture similar to the OSI model of data communication. Possible layers are: handheld ⇔ in-vehicle ⇔ roadside systems, and physical ⇔ regulation ⇔ coordination ⇔ planning ⇔ link ⇔ network. Their scope goes from controlling vehicle dynamics, manoeuvring, HMI, V2X, … over path/network/congestion control (platoon sizes, route assignments), … towards global and locally distributed controllers.

In this respect, Helbing also provides a classification of traffic management systems, as shown in Figure 2.1:

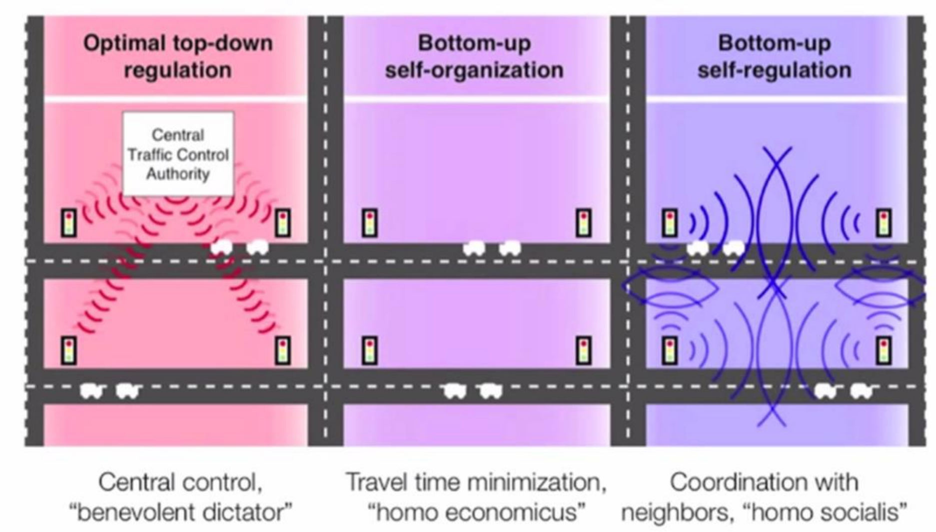

Figure 2.1: Classification of traffic management systems (reproduced after Kesting et al., 2008).

Finally, the emerging concept of Traffic Management as a Service (TMaaS) should be discussed in more detail. This concept found its root in the other existing ‘as a Service’ trends that are related to cloud computing, such as Mobility as a Service (MaaS), Platform as a Service (PaaS), Monitoring as a Service (MaaS), Communication as a Service (CaaS), Software as a Service (SaaS), Infrastructure as a Service (IaaS), ... to even the all-encompassing Anything as a Service (XaaS), as retold by Hendryx (2011). The newest incarnation in this group is TMaaS, which goes beyond a simple in-car delivery of traffic-related information. The idea that traffic management can be furnished as a private service is quite unique. Actually, such cloud-based system architecture provides the perfect means for almost one-on-one communication between individual road users and road operators. As an example, we highlight the work done by a public-private cooperation in The Netherlands, called ‘Field trial Amsterdam’ (van Beek, 2016). There, a group of private companies provided a back-end that interfaced with existing road operators’ and policy makers’ systems to obtain traffic information on a specific region in The Netherlands, upgraded with their own data stemming from sensors such as FCD. The group provided traffic management for the region during a special weekend that had several events occurring simultaneously. They received permission to update the available VMS panels, route traffic within the regions, and even communicate with individual road users by means of Facebook Messenger, WhatsApp, Twitter, and even a specific app-service that had over one million subscribers to provide in-car virtual VMS information. The results were a higher quality of traffic management, as more data sources were accessed, more qualitative data was used, and more users were reached with individual advice.

Similarly, the city of Ghent in Belgium is experimenting with the TMaaS paradigm[1], with EC-funding under the umbrella of the Urban Innovative Actions (UIA) initiative. In light of this, the EC-subsidy will also allow private start-up companies to grow, and lend their services to the city within their vision on mobility. These companies include digital map makers, communication providers, smart mobility experts, displays and LED-screens, cloud platform functionality, ... The central operation is a platform – the virtual traffic centre of Ghent – that collects data coming from all travel modes (public transportation by all means, walking, cycling, car traffic, ...), analyses them, and finally sends individual advice to its users taking their preferences into account. At current however, the platform is more oriented towards disseminating dedicated information to end-users (travellers, commuters), mostly uni-modal, with little to none true traffic control involved.

Note that the idea of TMaaS was also conceived in light of vehicular ad-hoc networks (VANETs), as described by Joshi et al. (2015). There, real-time services such as vehicle tracking, lane changing, accident detection, ... are pushed into a cloud, via a data service that carries out the data transfer from vehicles to the central cloud, which can be accessed again. Their model was also simulated using the microscopic traffic flow simulation 'Simulation of Urban Mobility' (SUMO) and the Network Simulator 2 (NS2), which are also used within the TransAID setup.

Note that TMaaS is at current mostly communication–oriented, in the sense that they intend to disseminate traffic information to individual road users. In our view, a truly full system for traffic management would also encompass a layer that actually 'manages' the traffic (albeit automatically).

2.2 Coordinating CAVs

The trend towards more cooperative systems is well-suited for enhanced traffic management. The communications both among vehicles (V2V) and between vehicles and infrastructure (V2I) are bringing about a paradigm shift in the way traffic is managed. Instead of the classic approach, whereby large groups of road users are targeted, we can now – at a sufficient level of penetration of cooperative vehicles – target vehicles individually. Such 'smart' vehicles become both sensor and actuator in a control system. The challenge now is to make sure that this individual approach (addressing the commercial software of the vehicle itself) does not harm the collective interest. Within this apparent public-private partnership, the government (or local traffic controller) will play an important role via its traffic centre(s) that need to align both the interests of the network and those of individual travellers. If this traffic management is not done properly, then intelligent vehicles may lead to inconvenient traffic flows, decreasing the overall efficiency of the system and even lead to an increase of congestion.

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 (2017). There they typically equip the roadside with some communication and interaction facilities based on the European CAR 2 CAR ITS-G5 (Wi-Fi-p) standard, and then we are not even talking about 3G/4G/5G ubiquitous cloud connectivity. There are various overarching projects, such as C-ITS Corridor, InterCor, Compass4D, Talking Traffic, … or even the C-Roads Platform signing a Memorandum of Understanding (MoU) for a closer collaboration between the automotive industry on the one hand and the road infrastructure providers/managers on the other hand. This will, in turn, facilitate the uptake of the so-called Day 1 and Day 1.5 services (the former are typical hazardous location

[1] https://www.trafficmanagementasaservice.com/

notifications, and the latter contain more specific mobility-related information; see also Appendix B in Section 8 for a detailed list). Bridging these technological and managerial evolutions with automated driving requires a next step to be taken. The will is there, but the means are still lacking. Opening public roads for private testing of automated vehicles requires changes in both legislation and infrastructure. Once these hurdles are taken, a next step will consist of moving certain services out of the portfolio of classic traffic management by the government, and into the hands of private service providers.

Translating traffic management measures into actions taken by individual vehicles requires an approach of direct interference with for example the Advanced Driver Assistance Systems (ADAS). One system that can be controlled in this way is the adaptive cruise control (ACC, getting a cooperative adaptive cruise control (C-ACC) by adding the communication feature). Via the state-feedback mechanism of model predictive control (MPC), a traffic management system can – in real-time – direct vehicles towards desired behaviour, i.e. keeping certain distances as described by Wang et al. (2015). The MPC mechanism performs optimal control repeatedly over a limited, rolling time horizon. At this point, the system could also weight its decisions as to whether or not to let the individual interest take priority over the societal interest. This is very closely related to user equilibria versus system optima. Moreover, such a system should also be able to cooperate with non-ACC equipped vehicles, something which is essentially the case in the various vehicle mixes on which we will allow TransAID to operate. Note that the same also holds true for a more intelligent version of an intelligent speed adaptation (ISA) mechanism.

Managing traffic in this individual way will also lead to a trade-off in the expected outcome. Take for example KPIs such as traffic safety on the one hand, and vehicle throughput on the other hand. Longer following distances lead to higher space and time headways, which improve traffic safety but are in se detrimental to the capacity of a road as that consequently decreases. However, the more C-ACC-controlled vehicles there are in a traffic stream, the longer a capacity drop can be postponed. One way to make this happen is by coupling roadside infrastructure such as VMS panels to individual vehicles' C-ACC systems. The global controller is able to estimate and predict traffic conditions on the entire road, and constructs certain schemes to temper congestion waves; this is then in turn formulated as advice to the vehicles' C-ACC systems. In total, this will allow the zone of control to be extended much further beyond the human visibility of a VMS panel, thereby allowing traffic to react more quickly to the changing context, even reducing the global travel time in a network.

Coupling roadside infrastructure to the vehicles as the next level/generation of traffic management approaches ties in with the intelligent transportation systems (ITS), 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 (2011). The neat thing is that the information can flow in both ways: a more global traffic management system can relay its control decisions to the individual vehicles, thereby being able to control a large amount of actuators, but it can also obtain information from all these probes, thereby having access to a more detailed state of the traffic flow. Within this setup of traffic management, there are various degrees of sensing and actuating, directly related to the vehicle mix of (non-) cooperative/connected/autonomous vehicles and the level of automation (cf. SAE levels (see Appendix 7). In a first instalment, these traffic management systems inform a driver via a human-machine interface, HMI, to provide advices or warnings. A semi-automated system can take partial control of vehicle manoeuvers (think ISA, forward collision mitigation/avoidance, …). A fully automated system takes complete control of vehicle operations and eliminates the driver from the control loop (cf. fully automated adaptive cruise control).

With respect to the advice that a traffic management system may give to (fully) automated vehicles, the task of platooning provides a promising approach. Vehicles are arranged in closely spaced groups, called platoons, having a single leader and a group of followers. Collisions are avoided by having small intra-platoon and large inter-platoon spacing. Another approach is to rely on the fully automated nature of vehicles, allowing them to self-organise and employ a distributed collective intelligence among the automated vehicles, with no influence or control from the roadside infrastructure. Clearly, the latter is less desirable for policy makers as there is no more active way to control traffic and to steer the system to a predefined set point (whether or not that is a user equilibrium or a system optimum). The main measures that can be taken to achieve the first approach are adaptive cruise control (C-ACC), intelligent speed adaptation (ISA), and dynamic route guidance.

In light of the transition towards more and fully automated vehicles, several questions need to be answered, e.g. as asked by Blythe (2015): "*What is the remaining role for infrastructure?*", "*How will traffic management evolve?*", and "*How will these evolutions impact road safety?*". Key challenges are moving from purely technical ones (i.e. how to implement the systems) more to regulations, liability, and acceptance. Current C-ITS systems focus on hazard warning (via V2X), data collection, in-vehicle signage for current/recommended speeds, red-light violation warning, incidents, route and other guidance, energy-efficient intersection control, …

The degree to which connected and automated vehicles are present in traffic flow is an important determinant for the success of modern traffic management strategies. 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 (2017) and Akkermans et al. (2017). As it is still early day, it is hard to foresee how the future will unfold in this respect. Nevertheless, we can expect that in countries that already have extensive road networks, the segregation of automated vehicles seems hard to become reality, aside from some limited cases (like bus shuttle services running on private premises). In addition, equipping these networks with the necessary V2I infrastructure may prove to be quite expensive (again, aside from certain specific locations which are typically funded on a project trial basis), and that is not even talking about international interoperability. The upshot of the accelerated penetration of automated vehicles within traffic streams is that policy makers and road infrastructure providers will have to take their responsibility in having to adopt adequate and enhanced standards of road maintenance.

Dealing with mixed traffic is a topic of its own, whereby several alternatives exist. One is to always physically separate any connected/automated vehicles from the other road users, or to only separate them at specific locations, or mixing them with an incurred transition of control from a higher level of automation to a lower one, possibly even returning (full) control to the human driver. The most efficient way for traffic to propagate would be to reserve dedicated lanes to highly automated vehicles, albeit that this is a costly solution. In case this is not done, other non-automated vehicle drivers must take into account the effects their automated counterparts have on the traffic flow and the behaviour they exhibit. This requires defining acceptable behaviour of automated vehicles in relation to other road users, for example regarding their different braking characteristics and their greatly reduced headways. A solution may be to have highly automated vehicles in their own lanes, but to require them to transition control to a lower level whenever no dedicated lanes are available (which can also of course happen in case external reasons such as snow or heavy rainfall are present). Properly suited infrastructure requires giving attention to roadside communications, traffic signals, clarity of road markings, signals, and signage, and segregated infrastructure.

The collaborative approach for automated vehicles is also high on the agenda for future traffic management systems. Shifting away from ‘each to their own’ autonomy becomes paramount in order to optimise road networks and take full advantage of the evolution towards full automation as described by Hart (2016). The sharing of data is a crucial aspect in this, and having access to highly detailed digital maps may very well prove to be a necessary requirement. It presents itself as an extra sensor, and the intelligence contained therein may even prove to be required when dealing with rerouting on a network level. Furthermore, care must be taken when mixing vehicles, in that human drivers also rely on safety measures such as eye contact, which are absent in the case of automated vehicles.

Coupling traffic management to communication protocols was done by Novaes et al. (2017), where they created VANETs in a simulation of the San Andreas multiplayer platform. Their focus lies on replacing classic traffic lights such that intersections can be navigated by AVs more efficiently. Each intersection manages the crossing of vehicles itself, via the exchange of UDP packets. This approach with using VANETs was also used by Santamaria and Sottile (2014). Their so-called smart traffic management protocol takes advantage of the IEEE 802.11p standard, whereby each road is equipped with several sensors that are responsible for the monitoring of the traffic situation. Preventive actions can then be taken based on the spreading of information throughout the network. This allows the system to more easily and quickly reveal congestion within an urban city environment. The traffic management systems itself is then described as an entity external to the VANET, that rearranges traffic along lanes and roads to avoid high congestion levels.

Finally, the work done in the Traffic Management 2.0 Task Force, as reported by Tzanidaki and Pelfrene (2016) 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. To achieve this, they propose a set of common interfaces, principles, and business models to facilitate the exchange of data between vehicles and a traffic management centre. The cycle of tasks then becomes more complex, as we now need to take several different steps into account, going from data collection, over data processing to implementation. Each of these has a rich set of sub steps, being V2I, statistics and modelling, control strategies, routing, I2V, and navigation systems, to name a few. Traffic management then revolves around the concept of ‘active moderation’, by which traffic centres can use the communication channels of service providers and influence, e.g., routing. The latter is done by influencing drivers either via road signage, apps, in-car personal navigation devices (PND), and even direct access to the vehicles themselves. Clearly, this type of control goes beyond the setup of a (simple) architecture, but requires an organisational structure in which all stakeholders take part, with processes clearly defined between them. Even though the Task Force mainly highlights questions that warrant further research, they make an interesting end observation: to successfully implement traffic management and road automation, we will need to have a classifying scheme for the infrastructure and the road networks. This will allow automated vehicles to ‘know’ specific characteristics of the various road segments. As a starting point they refer to the iRAP’s Road Protection Score methodology.

2.3 Artificial intelligence

Artificial intelligence (AI) can broadly be classified into three levels:

- Artificial narrow intelligence (‘weak AI’)
    - Very narrow, specific purpose
    - Big Data and complex algorithms (chess/Go players, Facebook wall, …)
    - Will not pass the Turing test
- Artificial general intelligence (‘strong/true AI’)
    - AI thinks as humans do (incl. intentionality)
    - Machines that are good at doing what comes easily for humans
    - Eventually learns and upgrades itself, on its own
- Artificial superintelligence
    - The technological singularity[2]
    - Cannot be easily ‘turned off’

The background of AI for traffic control is typically centred around the study of ‘intelligent agents’ (optimisation), having the goal to mimic cognitive functions learning / problem solving. The techniques used are multi-objective/level optimisation, (fuzzy) reasoning engines, multi-agent systems (MAS), artificial neural networks (ANNs), reinforcement learning (RL), and classification and regression. In general, we talk about machine learning through statistics. Some key ingredients here are incremental problem solving (including learning), real-time adaptation to changing context/environment, self-analysis (success ⬄ failure at tasks), memory (short- and long-term storage), and coping with large volumes of data (cf. Volume/Variety/Velocity/Value/Veracity). The scientific field of AI had its highs and lows: there were ‘winters’ with lower activities and toned down expectations, whereas nowadays we encounter a revival through the analysis of large datasets and deep learning techniques. AI is also including more ‘social’ aspects, whereby the perspective is shifting towards the individual (informing), there is input data for personalised services (Twitter feeds / WhatsApp / Facebook traffic-related content, on-demand ride matching, Waze / Google Maps probes, various floating vehicle data, C-ITS, …), and even social traffic management (leveraging the power of the community and accomplishing large-scale behavioural changes).

Currently, AI is mostly found in traffic light control and congestion / queue length predictions. Within the automotive sector we find it mostly in traffic sign and context recognition, ISA, route guidance, … There remains however a large theory-practice gap (experimental ⬄ mainstream), whereby only limited advancements are exploited in the field, AI is currently mostly used as a building block, it has difficulty in dealing with long platoons and the scalability (going from a single freeway to network-wide coordination).

Most of the control settings that use AI techniques typically test and compare several of them in a virtual setting, using some performance measure to determine the best technique. The link between AI and autonomous driving for example seems obvious, and is deemed to be one of the first domains in which the general public will be asked to trust the reliability and safety of an AI system, according to Grosz (2016). Typically, evolutions are foreseen at the (sub)microscopic level (i.e. ADAS such as parking assistance, lane departure warning (LDW), ACC, blind spot monitoring, lane changing, …), then AVs, and transportation planning on a higher, more tactical level, in order to optimise services (bus and subway schedules), dynamically adjust speed limits, apply smart

[2] This event occurs when AI abruptly triggers runaway technological growth; the AI would enter a string of self-improvement cycles, with each new and more intelligent generation appearing more and more rapidly, causing an intelligence explosion and resulting in a powerful superintelligence that would, qualitatively, far surpass all human intelligence.

pricing, optimise traffic light timings, prediction of individuals' movements by the traffic management center, ...

One group of smart traffic management systems uses techniques to mimic human reasoning in real-time, based on large quantities of available and up-to-date data. The methods adopted are based on fuzzy expert systems (FES), artificial neural networks (ANN), and wireless sensor networks (WSN). Compared to the more static systems which provide a simpler method of automatically controlling traffic, the big difference and bonus here is that they furnish more flexibility at urban junctions and with non-uniform traffic flows. From the research done by Hawi et al. (2015), it appears that for a learning or adaptive system, ANNs prove to be the best approach. For a system that just routes traffic based on real-time data the FES seems to be the way forward. For the latter, WSN can provide a cheaper alternative.

Similarly, Rass and Kyamakya (2006) defined the types of optimisation required for different technical control methods (traffic signals, dynamic signposts, and navigation recommendations). This leads to the use of expert systems that work rule-based (including fuzzy logic), self-adapting algorithms (artificial neural and Bayesian networks, genetic algorithms), and autonomously acting systems (agent-based systems). Many such traffic control systems use a so-called predict-and-control approach. The latter mentioned agent-based approach was also researched by Roozemond (1998), citing the benefit of the pro-active and re-active nature of the agents, and concluding that further real-life tests are necessary. Wang (2006) also used a multi-agent system as a real-time traffic control system, exhibiting global coordination and control on an autonomy-based view of the traffic streams in cities, thereby anticipating congestion and dynamically selecting intelligent traffic control strategies. The latter is coupled with the necessary real-time communication requirements and a sufficient level of fault tolerance. Strategies for traffic control are relayed to the agents, which then choose the best scheme according to their own real-time situation. Agents in this respect are typically vehicles, intersections, road segments, … A similar approach to multi-agent-based intersection control was proposed by Au et al. (2011), showing how travel times and emissions were drastically reduced. The main means of achieving this was that agents are allocated slots to travel the intersection, after they have requested a traversal.

Regarding traffic lights and intersection control, there are very few real-life implementations in contrast to the numerous, more academic case studies. Lämmer and Helbing (2009) described the control of traffic lights in urban road networks, with a trade-off involving strict coordination on the one hand (for regular services, green waves, continuous flows, …) and flexibility on the other hand (for incidental occurrences, public transport scheduling, demand responsive service of variable inflows, …). This was tested in a simulation environment in VISSIM and custom-made Java software, with 13 traffic light controlled intersections that each act locally but communicate with each other to achieve stability. Thinking about agents, and taking this one step further, was done by Renfrew (2009), who used ant colony optimisation techniques to achieve better fully actuated controls of traffic lights under conditions of high traffic demand. More recently, Isele et al. (2017) used deep reinforcement learning to allow AVs to navigate unsignalised intersections without exterior interaction. The point there was that while it is hard for AVs to handle those kinds of intersections, it is suboptimal to do it via rule-based systems. Therefore, their techniques outperform the more classic approach, based on metrics such as the time-to-collision. Interestingly, the approach has a downside in that it waits until vehicles have cleared an intersection, missing many opportunities for crossing. This technique with reinforcement learning has also been used in the MARLIN project by El-Tantawy and Abdulhai (2011) for controlling traffic lights in simulations of Toronto and Burlington. Note that they classify control algorithms in various levels, similar to the SAE levels for autonomous driving. Level 0 is fixed-time and actuated control (TRANSYT, 1969), level 1 is centralised control with off-line optimisation (SCATS, 1979), level 2 is centralised control with on-line optimisation (SCOOT, 1981), level 3 is distributed model-based control (OPAC/RHODES, 1992), and level 4 is the MARLIN system, i.e. distributed self-learning control.

Traffic management by itself using AI is rarer to be encountered in a broader setting. Gilmore and Elibiary (1993) provided an approach for this, by using a so-called distributed blackboard system whereby 'knowledge sources' exploit rule, frame, script and neural network representations to solve individual traffic management problems that appear on a blackboard data structure. The resulting traffic management decisions are then implemented and evaluated through simulation.

In this research, Gora (2015) proposed to use a simulation-based approach to traffic management pertaining to CAVs, with the advantage that large numbers of configurations of traffic management parameters can be ran through simulations, with the best one being selected.

Furthermore, Wu et al. (2017, 2017 and 2017) studied the emergent behaviours in the presence of mixed autonomy. They formulated a mixed-autonomy traffic problem and proposed a computational framework and architecture (Flow) for deep RL in traffic control with a reward function to encourage high system-level velocity. With the use of the model-free RL method vehicular velocity could be maximised by effectively and efficiently forming the vehicle spacing and traffic could be stabilised with the presence of few automated vehicles. Different network configurations, such as single lane, two lanes, a priority rule-based intersection, various penetration rates, stabilising traffic, platooning, and tailgating, were used to study emergent behaviours. They also demonstrated the selected polices, i.e., platooning, stabilisation and efficient vehicle spacing, with the use of the proposed RL method, coupled with the microscopic traffic simulation SUMO. Moreover, the concept of state of equivalence classes was introduced for improving the sample efficiency, which is often an issue in machine learning.

2.4 Conclusion

Based on the information presented in the previous paragraphs regarding the state-of-the-art for traffic management, we observe that there are quasi no (readily available) implementations of more advanced and/or generalised traffic management schemes that take higher degrees of vehicle automation into account. Most current research on this topic focuses on various aspects, such as solving partial problems/bottlenecks with specific measures (e.g., a new type of adaptive cruise-control, intersection management, a different kind of traffic light optimisation, creation of vehicle platoons, wireless communication to the driver/vehicle, …) and providing insight for the potential of autonomous vehicles in traffic management. In itself, all these solutions are very fine and usable; however, there are no experiments / setups whereby these solutions have to come together to provide an answer to traffic management on a higher level, allowing the interplay between all the various solutions to lead to a better system performance.

3 Traffic management procedures and protocols

3.1 Background

3.1.1 Goals, policies, and strategies

In general, traffic management can have the following goals:

- Minimise congestion
- Improve network capacity
- Improve network resilience against disturbances
- Manage demand
- Obtain more efficient logistics
- Improve safety
- Reduce the impact on air quality
- Support particular modes of transport (public transport, soft modes, …)

Once the goals are defined, authorities can then define policies based upon these, e.g.:

- Make polluters pay
- City access restrictions
- Encourage electric vehicles
- Encourage soft modes, public transport, …

In this step, politicians have to take into account what is practically publicly acceptable, or if the public can be persuaded to accept it in case of a new policy.

In turn, these policies are then implemented via a choice of tools/strategies, e.g.:

- Low-emission zones, road user charging, …
- Subsidies for purchase of electric vehicles
- Installing chargers for electric vehicles
- Nudging towards soft modes
- Subsidising public transport

In larger cities, the wider political imperatives are implemented via a **traffic management centre** (TMC [3]). Smaller cities run on the principle of minimal intervention. Regarding the implementation/deployment of such tools, we note there is a financial pressure on policy makers and authorities. This combined with a lack of resources makes it difficult to switch to a brand-new ITS infrastructure. Hence, there is an impact on a city's ability to adopt new technologies quickly. In such cases involvement from the private sector can help. A good way of doing this is via a buy-in, but against predefined standards, thus both saving cost and avoiding vendor (proprietary) lock-in. The idea then is that by doing for example a market consultation, local authorities can obtain a competitive offer that balances price and quality. Keeping the standards in place then ensures that the solution from a selected vendor is not uniquely maintainable or extendable by that same vendor. If it was the case, then it might pose a problem later on when the vendor either stops its activities, changes its pricing during contract renewals/renegotiations, or makes the local authority totally dependent on it. Changing vendors at that stage would then incur (possibly high) switching costs which are to be avoided.

[3] An equivalent term would be 'traffic control centre' (TCC).

3.1.2 Traffic management from an EC perspective

Regarding the implementation of C-ITS in urban areas, the EC's C-ITS platform[4] identified a set of common barriers to urban C-ITS implementation:

- Lack of knowledge about C-ITS (difference with traditional ITS)
- Lack of awareness of the full potential and benefits across the entire urban stakeholder chain
- Lack of clear business models for urban applications
- Lack of knowledge about the evolving roles and responsibilities of different stakeholders
- C-ITS integration with existing legacy systems

Keeping the above barriers in mind, the deployment and integration of C-ITS services can be looked at from the classical theory of technology adoption as explained by Rogers (1962, 2003). In this context, it depends who will be involved early on, and who will rather follow and/or adopt best practices encountered elsewhere. Within this framework, the following adopter categories are identified:

Table 1: Overview of adopter categories, distinguishing between innovators, early adopters, early and late majorities, and laggards. The table was reproduced after Rogers (1962).

Adopter category	Definition
Innovators	Innovators are willing to take risks, have the highest social status, have financial liquidity, are social, and have closest contact to scientific sources and interaction with other innovators. Their risk tolerance allows them to adopt technologies that may ultimately fail. Financial resources help absorb these failures.
Early Adopters	Early adopters have the highest degree of opinion leadership among the adopter categories. They have a higher social status, financial liquidity, advanced education, and are more socially forward than late adopters. They are more discreet in adoption choices than innovators. They use judicious choice of adoption to help them maintain a central communication position.
Early Majority	The early majority adopts an innovation after a varying degree of time that is significantly longer than the innovators and early adopters. They have above average social status, contact with early adopters, and seldom hold positions of opinion leadership in a system.
Late Majority	The late majority adopts an innovation after the average participant. These individuals approach an innovation with a high degree of scepticism and after the majority of society has adopted the innovation. The Late Majority is typically sceptical about an innovation, has below average social status, little financial liquidity, in contact with others in late majority and early majority, and little opinion leadership.
Laggards	Laggards are the last to adopt an innovation. Unlike some of the previous categories, individuals in this category show little to no opinion leadership. These individuals typically have an aversion to change-agents. Laggards typically tend to be focused on 'traditions', lowest social status, lowest financial liquidity, oldest among adopters, and in contact with only family and close friends.

[4] As of September 2017.

Within the diffusion of innovations, successive groups of consumers who adopt new technologies are typically assumed to have the distribution within a population as indicated in Figure 3.1 (graph reproduced after Rogers (1962)).

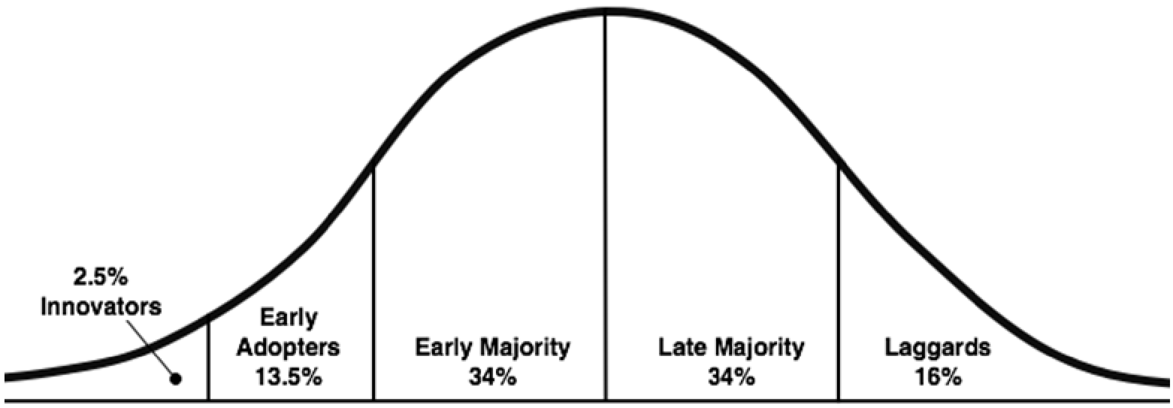

Figure 3.1: Rogers' (1962) bell curve of product adoption, outlining the percentage of the market who adopt a product.

Regarding the adoption of traffic management measures in a more integrated, holistic approach, experts from the CAPITAL (2018) project are convinced that integration will very unlikely be a big-bang implementation, but rather a migration from current systems, requiring a mix of public and private stakeholders.

An example of an initiative for a more harmonised deployment of ITS services is the EasyWay project, as explained by Arnaoutis (2009). This project serves as an example of a pan-European implementation of (in broad view) traffic management services to achieve a set of predetermined policy goals. To maintain standards, a cross-border cooperation was initiated between eight Euro-Regions (CENTRICO, STREETWISE, ITHACA, SERTI, ARTS, CORVETTE, CONNECT, VIKING). They facilitated the integration of all new Member States, which also reinforced the co-operation between the existing participating countries by providing a new integrated framework with clear objectives and reporting methods.

In a nutshell, EasyWay is a project for Europe-wide ITS deployment on main Trans European Road Network (TERN) corridors, with more than 21 member states involved. It was driven by national road authorities and operators with associated partners including the automotive industry, telecommunications operators, and public transport stakeholders. The programme set out clear targets and identified the set of necessary ITS European services to deploy (i.e. traveller information, traffic management and freight and logistic services). It comprised an efficient platform that allowed the European mobility stakeholders to achieve a coordinated and combined deployment of these pan-European services. From a policy perspective, EasyWay set out three (European) objectives: (i) increase road safety, (ii) increase mobility and decrease congestion, and (iii) decrease the transport burden on the environment. The project adopted certain traffic management services such as dynamic lane management, ramp metering systems, incident warning and management, and speed control, all bundled in over 30 traffic management plans, systems, and tools. Their connected ICT infrastructure allowed for fixed traffic monitoring stations, floating vehicle data, travel time monitoring, automatic incident detection, cameras, and road weather monitoring stations. Interestingly, on this scale of deployment they used around 350 traffic information/management/control centres. As a result, EasyWay led to 5% savings in accidents, a 6% reduction in congestions, and a 1.5% reduction in CO_2 emissions.

On a larger policy level, we note the specifications of the **ITS Directive 2010/40/EU**. This was a legal framework adopted on 7 July 2010, having the general goals of: (i) accelerate development of innovative transport technologies, (ii) establish interoperable and seamless ITS services, (iii) Member States decide on where to invest in. It pans out into four priority areas and six priority actions.

- Priority areas:

  1/ Optimal use of road, traffic and travel data

  2/ Continuity of traffic and freight management ITS services

  3/ ITS road safety and security applications

  4/ Linking the vehicle with the transport infrastructure

  5/ Data protection and liability

  6/ European ITS coordination

- Priority actions:

  1/ EU-wide multimodal travel information services

  2/ EU-wide real-time traffic information services

  3/ Minimum universal safety-related traffic information free of charge to users

  4/ Interoperable EU-wide eCall

  5+6/ Information & reservation services for secure parking for trucks

In similar spirit, the **C-ITS Platform** Phase I and II has the goal to move towards a national and local ITS framework. This entails the translation of the Directive into a National ITS Strategy via a national **ITS Action Plan**, and a further translation into a City ITS Strategy via a **Sustainable Urban Mobility Plan** (SUMP).

In order to develop such SUMPs, the following steps are relevant in light of our own view on the implementation of traffic management services:

- Define objectives
- Analyse the mobility situation and develop scenarios
- Develop common vision
- Set priorities and measurable targets
- Develop effective packages of measures
- Agree on clear responsibilities (and allocate budgets)
- Build monitoring and assessment into the plan

Importantly, policies are defined by a broad range of actors. In this light, the following list presents a value chain of stakeholders that is useful for consideration:

- Mayors/politicians
- City administration and planning
- Transport ministries
- Road authorities
- Road operators
- Automotive industry
- Service and content providers
- Drivers/inhabitants
- Personal and goods transport
- Logistics and delivery
- Chamber of commerce

3.2 Outline of the traffic management framework

3.2.1 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 a minimum risk manoeuvre (MRM). The location of such an event is referred to as the Transition Area (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**. This 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 3.2.

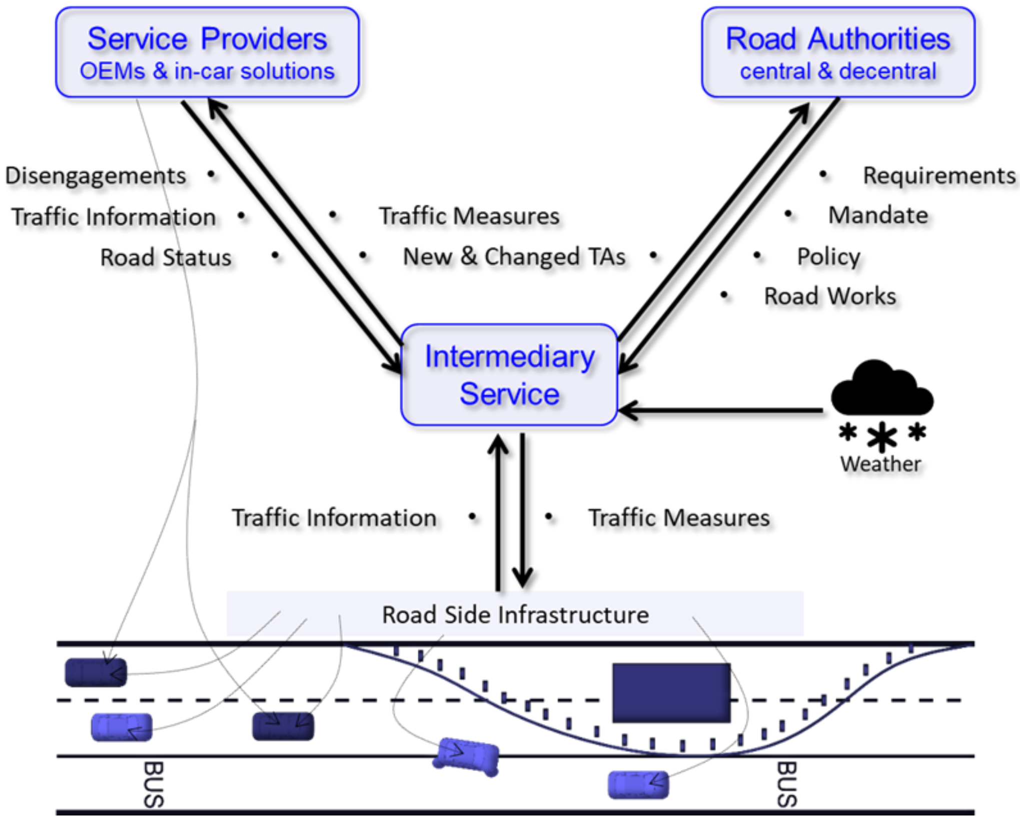

Figure 3.2: Schematic overview of TransAID's intermediary service approach.

Depending on the way the measures are developed within TransAID, the requirements of being able to dynamically deploy them can vary. Also, since we are still identifying TAs, the way to recognise those needs to be studied during the course of the project.

It is the goal to develop the concept presented above in upcoming deliverables of WP4 and use the concept to help steer the development of the measures in a clear direction. With the **added high-level management of TAs** in addition to **the development of measures on a local level**, we foresee TransAID measures can be more effective.

3.2.2 High- and low-level traffic management operations

Within the framework of traffic management (TM) in TransAID, we also assume there are a number of **road-side units**[5] (RSU) that each look at traffic in their immediate vicinity (their finite range stems – among other reasons – from the assumption of realistic communication capabilities). The **traffic management centre** (TMC) is then a logical entity that uses and communicates with these RSUs, as illustrated in Figure 3.3. In that sense, the RSUs aspire to have an as-good-as-possible view on their local situation (either through communication with connected vehicles, such as CV and CAV, or through information obtained from road-side detectors such as loop detectors, camera's, …), whereas the TMC – as a smart infrastructure – combines these in order to get the global picture. In light of TransAID's traffic management context presented in Section 3.2.1, the TMC is to be considered as the intermediary service.

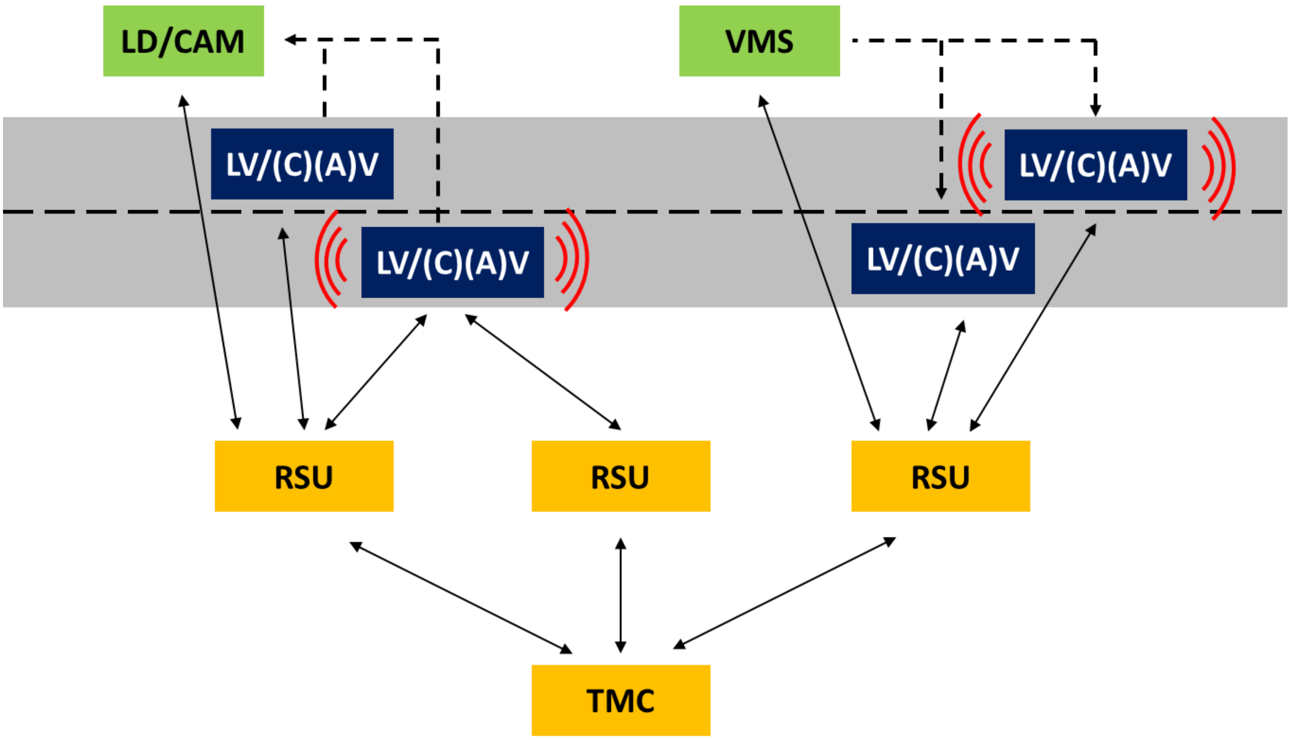

Figure 3.3: High-level overview of how the traffic management centre (TMC) interacts with the road-side units (RSU), in order to obtain information on the traffic stream as well as broadcasting measures.

[5] Note that all RSUs, as well as loop detectors, cameras, variable message signs, … are also road-side infrastructures (RSI), which is an umbrella term to denote this group of actors.

TransAID encompasses a set of services that can be deployed within a traffic management infrastructure to monitor and control a specific (inter)section of a road. In that sense, they can be considered as solutions to traffic control problems. The main goal of the research within WP4 is thus to address **which services are best deployed given a certain situation**. To that end, we follow a two-step approach, coinciding with the two iterations within TransAID:

- First, each service is considered separately and its **performance** tested under specific controlled conditions (i.e. the use cases). This directly ties in to the simulations that are to be done in Task 4.2 with results in D4.2.

- Secondly, based on the results from the first iteration the traffic management system chooses **which services to best use** given a certain situation.

A fundamental question to be tackled is where the **intelligence of the system** resides. On the one end of the spectrum we have a central intelligence that knows and controls everything itself, whereas on the other end there is fully distributed intelligence whereby all vehicles in the traffic streams act as individual agents. Various mixtures exist in between these two ends, whereby higher-level goals are translated into certain set points (these are predefined objectives that we want to reach), which are then communicated at a lower level to the individual vehicles which are themselves responsible for achieving the requested behaviour. Putting it more correctly, we rather talk about the **degree of interference** of the TMC with the vehicles, going from a very high level down to detailed specific inputs to the motor management systems of individual vehicles. Note that it is both quite improbable and infeasible to reach this latter level, as OEMs are typically not inclined to give (full) external access to their own CAN-buses.

Communication at the lower level is also dependent on the richness of the RSUs. On the one end they can be deployed as ‘thick clients’ that have the ability to perform more dedicated control and work in a higher standalone setting, whereas on the other end they can be set up as ‘thin clients’ that are by their nature more light-weight, energy-efficient, and consequently have a lower computing power thus limiting more their abilities for control, relying more on higher level inputs.

We therefore envision that the operation of the traffic management system works in turn on two levels:

- **Higher-level operation:**
    - There are a number of inputs, collected by the RSUs, related to **lane-dependent (i) volume and (ii) composition of the traffic streams**, (iii) derived measures like surrogate safety measures (SSM), and (iv) predefined policy goals. Inputs (i) and (ii) are obtained through road-side detectors, as well as via available sensing vehicles (by CVs and CAVs).
    - The inputs are sent to the TMC, which then decides what the best measures are (given a palette of services that can be used both standalone or in a combined fashion), given the current situation. As explained previously, we will in first instance look at each service separately by means of a selected use case and evaluate its performance, after which we can create recipes that – given a situation – select the best service.
- **Lower-level operation:**
    - The TMC broadcasts its information to the traffic participants, via the RSUs, which can be done in a broad way (e.g., by means of variable message signs that relate to groups of vehicles / road sections / lanes, in-car advice to the driver, or generally-defined advice such as a requested average time headway), or via dedicated communication (e.g., in-car advice specifically tailored per relevant vehicle). CVs and CAVs can in principle be directly addressed by the RSUs, whereas LVs and AVs should be addressed via the RSU signalling them through VMSs, traffic lights, ... Note that in the setup, the RSU clients can – as explained before – be either deployed as fully-controlling (thick) or relying on higher-level input (thin).

The previously described mode of operation can in turn trigger a (stable) feedback control loop, such that a certain higher-level optimality criterion (or a group of set points) can be met. This control should both be elegant and robust. As such, the control loop implements traffic management measures, simulates these, measures the impacts, and translated this into more optimal control actions to reach predefined set points.

Based on the previous descriptions, we consider TransAID's approach to traffic management to be a variation in the Traffic Management-as-a-Service (TMaaS) methodology (see also Section 2.1), establishing and guiding the communications between individual road users and road operators. Within this setup of TMaas, there is a high focus on the communication aspects, as traffic information is to be disseminated to (all) individual road users within the traffic stream

3.2.3 Compliance of automated vehicles to traffic laws

With the real-time coordinated instructions of a TMC, (C)AVs should drive adequately during their journeys. However, it is necessary to concern to what extent such instructions should/can be made, especially when concerning legal issues, i.e. whether or not traffic management should 'instruct' vehicles (and more specifically, autonomous ones) to force them into a situation in which they would be breaking the law. An example of this is a motorway with two or more lanes in each direction, and queue spillback occurring at an off-ramp. In some cases, vehicles will gather behind each other on the hard shoulder lane. This is a clear violation of traffic laws, but it is perceived as safer situation and outcome than if all of them would otherwise be blocking the rightmost lane of the motorway. Human 'resourcefulness' causes the LVs to self-organise themselves on the hard shoulder lane as opposed to just using the rightmost motorway lane. The fact that this happens is by itself a symptom of a (localised) infrastructural problem, whereby the existing capacity is optimally used by the majority of traffic. What should an (C)AV do in this case? Should it follow directly and append the queue on the hard shoulder lane (thereby breaking the law as it is forbidden to be used for regular driving), or should it miss/drive by the off-ramp, or should it rather stop on the rightmost lane, possibly creating a dangerous situation?

Another less obvious example is when there are dynamic lane assignments that are communicated to the road users via messages on VMSs. When lanes are 'crossed-off', some drivers still tend to ignore this and continue driving on the lane, even though it may lead to a fine. An (C)AV should be made aware of this. Or in another case, when so-called rush hour lanes are opened at certain times of the day, and traffic law requires everybody to drive on the right, an (C)AV may find itself on the rightmost lane. But, as not everybody is doing this, it may lead to dangerous situations in which the (C)AV is actually overtaking other vehicles on its left-hand side, which again is a violation of traffic law. In addition, there are also situations in which, e.g., weaving lanes, are not used as intended, with other vehicles possibly using them to take over other (long stretches of queued) vehicles, which leads to complicated situations.

The question then always remains: what is the required/expected behaviour of an (C)AV?

A possible way to resolve this dilemma is by having a classification of the traffic rules, distinguishing between types of rules as to whether or not they are allowed to be broken under specific circumstances. There are however numerous related issues that need to be dealt with, not in the least existing differences between countries' legislations. It is clear that we need more input on this, especially from the point of view of road authorities. Within the TransAID project we do however have a more controlled environment, in which we can at least make a choice to resolve these intricacies.

3.3 Use cases analysis in terms of procedures and protocols for LVs/CVs/AVs/CAVs

In the next sections, we explain the various implementations of traffic management for each of the services / use cases defined in WP2, i.e.:

- 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

The goal each time is to honour predefined policy goals, translated into certain safety and throughput characteristics of the traffic streams, as well as the prevention of transitions of control and avoiding the execution of minimum risk manoeuvres.

The 'right' traffic management measures are dependent on traffic conditions and the vehicle mix, as defined in deliverable D2.2 and updated in D3.1. We have reproduced the relevant tables in Appendix C.

The rest of this section details each of the selected use cases, with each time first a short recapitulation of the functional constraints / dependencies that need to be satisfied, as well as a spatial overview of the respective use case. We then place special emphasis on the context of the traffic measures, explaining in turn:

- **When do we need to apply the traffic measures?**
  The idea here is to understand under which traffic conditions the traffic measures should be applied, i.e. they are directly related to the current level of service (LOS). In TransAID we focus on LOS A, B, and C, for which the definitions are given in Appendix C. In order to assess whether or not traffic measures should be applied, we base ourselves on the information contained in deliverable D3.1, more specifically the results of the base line simulations and the situations for which we assess that traffic management is necessary. Defining when the traffic measures are applied is based on discriminating the local traffic situation, described in terms of the current vehicle mix and the LOS. An example is given with the following table, whereby the red-coloured cells indicate that traffic management is preferred:

Vehicle mix	LOS A	LOS B	LOS C
1			[red]
2			[red]
3		[red]	[red]

  The rationale behind this approach is that, under light traffic conditions, traffic systems can quite effectively organise themselves as evidenced by Hoogendoorn and Bertini (2012). In this case, this self-organisation of the traffic system is not per se 'intelligent', but can rather be defined by the rather simple dynamics of individual 'particles' that lead to complex collective macroscopic patterns. However, when congestion is on the horizon or even setting in, then the system is no longer efficient when let in its self-organising state (think of phantom jams, queue spillbacks, …). At this point, traffic management enters the picture. Note that, regarding the 'conduct' of the traffic streams, we assume a moderate driving behaviour. If feasible, we can investigate during the second iteration to what degree this influences the results.

- **Where do we need to apply the traffic measures?**
  Here we look at the spatial action horizon of the traffic measures, e.g. what is the extent of the transition area? At which point does the system need to inform vehicles/drivers? This is defined by looking at the spatial context of the use case and certain quantities that provide us with extra information (for example, queue lengths, local densities, average speeds, number of change lanes, …). The latter are not exhaustively listed, as their effectiveness will also be dependent on the performance of the simulations done in deliverable D4.2 where we will parameterise them.

- **How do we need to apply the traffic measures?**
  Once the when and where of traffic measures are known, the next step is to identify the operations of the traffic measures themselves. At this stage, we foresee this to be more descriptive and high level (i.e. what are available traffic management options and feasible extensions of them), whereas the real 'recipe' for the deployment of traffic measures will be specified, implemented, and tested together with the simulations in deliverable D4.2. The idea is that these recipes are given from the point of view of a traffic management centre, which will lead to the timelines described in deliverable D2.2 (which are mostly viewed from the context of the vehicles themselves). This will then also automatically take into account the time scales of events occurring to which a traffic management system must react and the expected response times of drivers are investigated.

As explained by Hoogendoorn and Bertini (2012), there can be – loosely speaking – four types of solutions identified within the field of traffic management:

1. Prevent spillbacks
2. Increase throughput
3. Effectively distribute traffic across the network
4. Regulate the inflow of traffic

TransAID is, depending on the use case under consideration, focused on all four of these. Examples are speed advice, which can control the inflow in the back of a traffic jam, and hence allow the jam more time to dissolve via its front and thereby stopping further upstream propagation of the wave (so less spillback is encountered). Reducing the inflow (and its speed) into a (portion of a) network can in turn help to increase the overall throughput in the system. The third approach to traffic management is for TransAID more related to those use cases that deal with merging and weaving areas, whereby traffic is receiving guidance information on a very local basis. The fourth approach ties in with the previous three, in that the goal here is to limit the global inflow, and hence preventing the traffic system to reach a tipping point by keeping the number of users in the network below a certain critical number.

Note that all traffic management measures are striving to reach a certain predefined setpoint for (a group of) KPI(s). An example of such an objective is to keep the minimum average traffic/network speed above 15 km/h, or to keep queue lengths within certain bounds.

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

3.3.1.1 Recapitulation of the use case

For this use case, we need to satisfy the following functional constraints / dependencies:

- It must be possible to prepare a path around the road works via the bus lane and have it available for the TMC before the road works start.
- The TMC must be able to distribute the path to CAVs.
- CAVs need to be able to receive and understand the path information.
- CAVs need to be capable of driving along the provided path.
- CAVs need to understand that they are allowed to drive on the bus lane via the path.
- CAVs need to be able to merge before or behind the approaching bus.

Spatial overview of the use case:

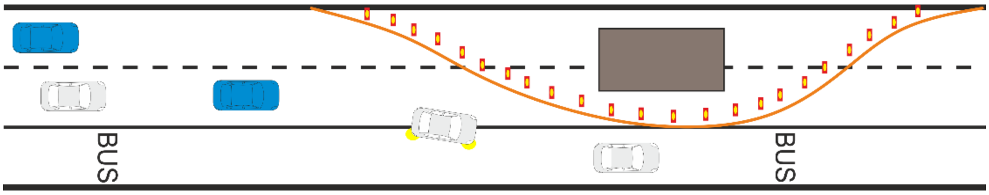

Figure 3.4: Schematic illustration of use case 1.1.

3.3.1.2 Context of the traffic measures

3.3.1.2.1 When to apply the traffic measures

Baseline simulation results from deliverable D3.1 indicated that impacts on traffic efficiency and dynamics increase slightly from LOS A to LOS B, but more dramatic within LOS C. For congested scenarios the baseline simulation results show constantly large queues building up right before the bottleneck by the subsequent lane drops. Congestion arises due to merging problems at the beginning of the construction site, which in turn is caused by latencies in take-over processes and consequently delayed lane change attempts by drivers in the post-ToC phase. As the traffic flow is not severely perturbed for low to moderate demand levels, we expect TransAID measures to be most effective for high traffic demands, as in LOS C, for the present scenario. However, since results also showed that a larger number of CAVs/CVs decrease the average speed and capacity, we may conclude that TransAID measures can also have a significant positive impact within LOS B given vehicle mixes 2 and 3. Moreover, for mixes that contain higher shares of connected vehicles it is more likely that measures using V2X communication can impose sufficient control to achieve an improvement.

Table 2: Baseline simulation scenarios (shown in red) that warrant the application of traffic management measures for Service 1.1.

Vehicle mix	LOS A	LOS B	LOS C
1			
2			
3			

3.3.1.2.2 Where to apply the traffic measures

The results of D3.1 might lead to the conclusion that a mere path provision next to the construction site might not be sufficient enough as a measure for congested scenarios. Therefore we distinguish between two sets of measures. On the one hand, we have measures to be taken in the close proximity of the construction site, having the goal of preserving a smooth traffic flow. And on the other hand, we have measures which aim at establishing an optimal arrival flow (see Section 3.3.1.2.3) already at a larger distance upstream of the bottleneck. Thus, we have:

1. Short distance measures, i.e. path provision and merging assistance close to the construction site.
2. Large distance measures, i.e. speed and lane advices to organise vehicle distribution and prevent over-saturation of the traffic flow at the bottleneck.

To provide a path around the construction site, mainly local and geometrical conditions have to be taken into consideration because traffic dynamics are less influential within the construction area. Parameters that have to be taken into account to determine an area for the application of measures are (i) average speed, (ii) lane change duration, and (iii) traffic density (see also use cases 2.1 and 3.1). In general, short distance measures are to be applied to support a zipper merge at each lane drop location. Long distance measures can be initiated as early as possible, that is at the horizon of the RSU or the maximal distance at which an opening of the special lane is feasible.

3.3.1.2.3 How to apply the traffic measures

As described in D2.2, TransAID measures aim to support this scenario by presenting a path around the road works as well as supporting the corresponding manoeuvres by giving speed and lane advices. Thus, the opening of the bus lane has to be communicated. Here, the exact implementation of this measure will be explained in deliverable D4.2. That is, an approved path can either be provided explicitly via waypoints, or by the higher level information that the bus lane is allowed for other vehicle types. The latter strategy leaves the utilisation of this information in their manoeuver planning to the CAV/CVs. After all we assume that AVs will behave more conservatively than human drivers, and require headways larger than which are usually provided by cooperative human drivers in dense merging situations. This strategy implies that AVs must be informed earlier than human drivers about the opening of the extra lane and should be encouraged to orient themselves rightwards. However, the amount of vehicles on the opened lane should not significantly exceed the number of vehicles on the middle lane to avoid an extensive backlog. Thus, a zipper support should be implemented close to the lane drop for the case that the share of AVs exceeds a certain level, which prevents assigning all of them to the rightmost lane. The zipper process can be smoothed considerably if vehicles on the target lane cooperate according to a central coordination applied via speed advices.

Hence, we have the following measures for this use case:

a) Communicate bus lane opening to CAVs (using I2V) prior to LVs (using VMS).
b) Provide lane change suggestions to gather primarily AVs on the bus lane.
c) Provide speed advices to prevent over-saturation of the flow close to the construction site.
d) Provide zipper support close to the lane drops.

Table 3: Estimation for types of traffic management measures depending on traffic conditions for Service 1.1. Estimated feasible application ranges are to be evaluated.

Vehicle mix	LOS A	LOS B	LOS C
1			(a) + (b)
2		(a) + (b)	(a) + (b) + (c)
3		(a) + (b) + (c)	(a) + (b) + (c) + (d)

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

3.3.2.1 Recapitulation of the use case

For this use case, we need to satisfy the following functional constraints / dependencies:

- The TMC must be able to detect the position, direction and speed of vehicles through collective perception.
- The TMC must be able to detect gaps in mainline traffic.
- The TMC must be able to estimate the optimal speed and lane advice for on-ramp merging CAVs and CVs and distribute that advice.
- The TMC must be able to estimate optimal speed and/or lane advice for mainline CAVs and CVs and distribute that advice.
- CAVs must be able to receive, process and execute speed advice and lane change requests.
- CVs must be able to receive and convey speed advice and lane change requests to drivers.

Spatial overview of the use case:

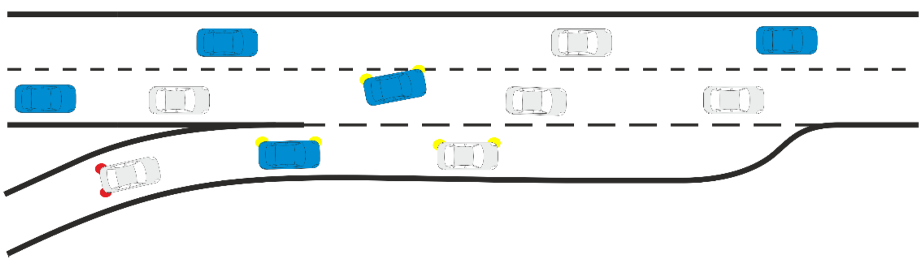

Figure 3.5: Schematic illustration of use case 2.1.

Due to the complexity of vehicle mixes in the iterative project approach of TransAID, the complexity of the congested traffic patterns also increases, which motivates the increasing usage of traffic management measures, especially the implementation of infrastructure-assisted schemes at transition areas. Among these control measures, speed advice, lane advice, cooperative merging, intersection traffic light control (refer to the TLC on the most adjacent upstream intersection of on-ramp), ramp metering, and ToC (MRM) for on-ramp vehicles can be adopted in use case 2.1.

3.3.2.2 Context of the traffic measures

3.3.2.2.1 When to apply the traffic measures

As defined in deliverable D2.2 and updated in D3.1, two dimensions are used to describe the prevailing traffic conditions, as explained at the beginning of Section 0. From the three vehicle mixes, we can see that on the one hand, these mixes are a simplified combination of possible actors (e.g., exclusion of AVs). On the other hand, they offer more extreme values (e.g., in vehicle mix 3, 90% of the vehicles are communication-enabled).

For simplicity and comparability, the compliance rate assumptions are as follows: the CVs and CAVs are 100% compliant due to their communication capabilities. The LVs are considered not reachable by traffic management measures. Therefore, they are regarded as obstacles that do not react to the measures and/or do not have possibilities for creating gaps. The cells in Table 4 show when we expect traffic management measures to be taken given the vehicle mix and level of service.

Table 4: Baseline simulation scenarios (shown in red) that warrant the application of traffic management measures for Service 2.1.

Vehicle mix	LOS A	LOS B	LOS C
1			
2			
3			

3.3.2.2.2 Where to apply the traffic measures

Figure 3.6 shows the merging schematic of the network for use case 2.1. In this schematic, the transition areas are not shown as in the baseline simulation. Instead, the layout is outlined with cooperative zones (both on the motorway and the on-ramp) and the merging zone. Since the main goal for this use case is to prevent ToCs/MRMs by implementing TransAID control measures, the transition areas in the baseline simulation are redefined here as cooperative/merging zones. The applicable traffic management measures that we are interested in will be actuated on these zones.

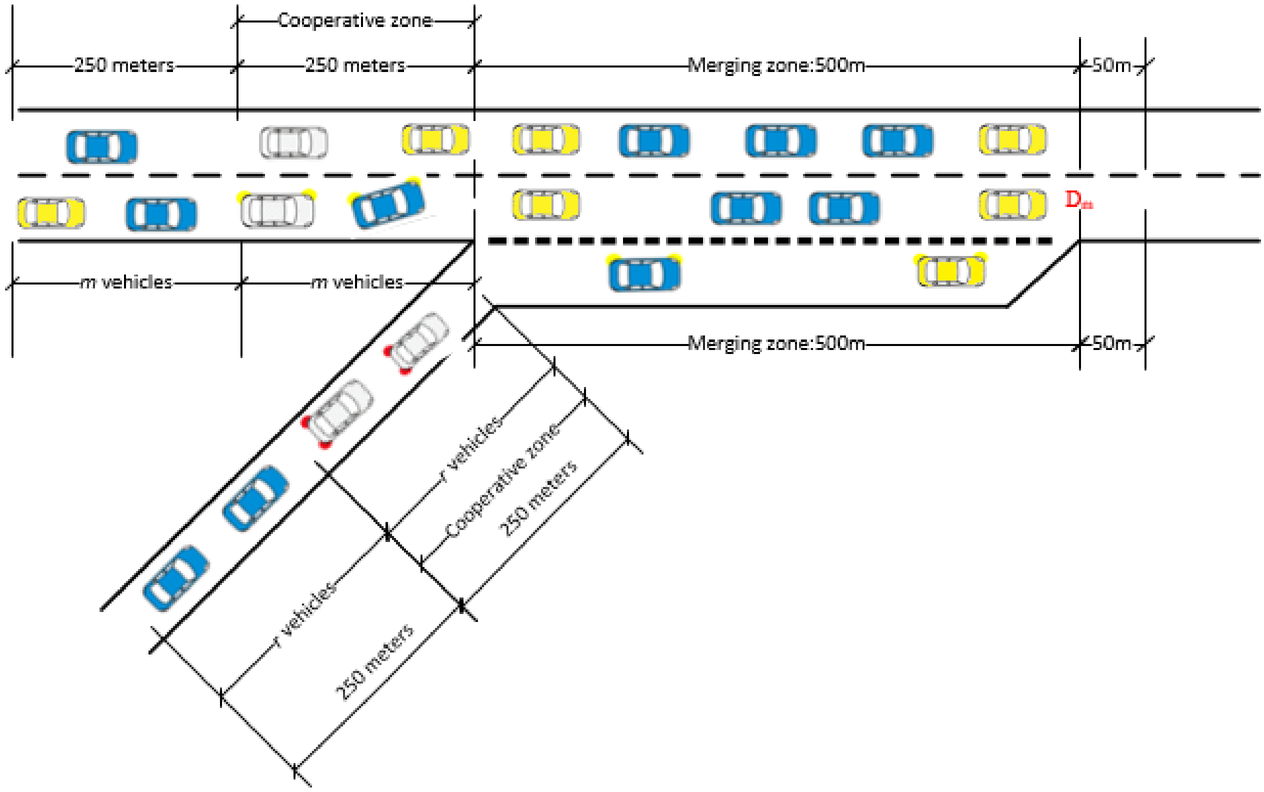

Figure 3.6: Merging schematic (cooperative merging system) of the network for use case 2.1.

3.3.2.2.3 How to apply the traffic measures

The list of traffic management measures that are applicable to use case 2.1 is as follows:

(a) None (as baseline, do nothing)
(b) Speed advice on the mainline in the cooperative and merging zones, e.g., 80 km/h
(c) Lane advice on the mainline in the cooperative and merging zones
(d) Cooperative merging strategy coordinated with upstream intersection TLC
(e) ToC and MRM for on-ramp vehicles when (b), (c), and (d) did not find acceptable gaps
(f) [optional: ramp metering]

In the following paragraphs we give a more elaborate treatment of these applicable measures:

(a) None

In this control measure, no traffic management measure is deployed. The situation stays exactly the same as baseline simulation. This is due to the fact that, when the traffic demand is low enough (e.g., LOS A), a specific traffic composition (e.g., vehicle mix 3) does not show any obvious disturbance in traffic flow and therefore there is no need for infrastructure-assisted traffic management measures (see also the explanation at the beginning of Section 0).

(b) Speed advice on the mainline in the cooperative and merging zones

In this traffic management measure, speed advice is given to CVs and CAVs on the mainline motorway in the Transition Areas. The compliance rates for CVs and CAVs are 100%. In other words, all CVs and CAVs on the mainline, passing the cooperative and merging zones, are reached and mandated to reduce speed from 100 km/h to 80 km/h. By adopting a lower speed than the posted speed limit, the traffic flow on the mainline becomes smoother. The phantom jams (shockwave congestion) are reduced and capacity on the mainline is increased. Since traffic demand on the mainline does not increase during one simulation, this will probably lead to more opportunities for the on-ramp vehicles (later on acceleration lane vehicles) to merge to the mainline.

(c) Lane advice on the mainline in the cooperative and merging zones

In this traffic management measure, lane advice of changing to the leftmost lane on the motorway when possible is given to CVs and CAVs on the mainline motorway in the cooperative and merging zones. The compliance rates for CVs and CAVS are 100%. In other words, all CVs and CAVs in the cooperative zone on the mainline should try to change from the right lane to the left lane; all CVs and CAVs in the merging zone on the mainline should try to change from the middle lane to the left lane. The lane advice of changing to the left lane in certain zones and creating gaps for merging vehicle is considered a direct way of gap-metering in the merging zone.

(d) Cooperative merging strategy coordinated with upstream intersection TLC

In this traffic management measure, we apply a cooperative merging strategy that coordinates with on-ramp upstream intersection TLC. It is assumed that the upstream intersection of the on-ramp can release a platoon of vehicles during a green-light phase. This group of vehicle is denoted with '*r vehicles*' 250 m upstream to on-ramp cooperative zone in Figure 3.6. At the same time, another group of '*m vehicles*' is identified 250 m upstream to mainline cooperative zone. The cooperative merging algorithm keeps calculating the optimal merging sequence in real-time for CVs and CAVs of these two groups of vehicles (LVs are considered as obstacles as they are not affected by this type of control). When '*r vehicles*' and '*m vehicles*' travel in the merging zone on mainline, the CVs and CAVs will merge according to the updated optimal merging sequence.

(e) ToC and MRM for on-ramp vehicles when (b), (c), and (d) did not find acceptable gaps

In previous traffic management measures (b), (c), and (d), all CVs and CAVs are 100% compliant to traffic management measures and did not perform ToCs or MRMs (as indicated in the baseline simulation). In this control measure, the CVs and CAVs on the on-ramp will perform ToCs and MRMs when the traffic management measures (b), (c), and (d) did not create acceptable gaps for them. Thus, this control measure can be considered as a fall-back strategy.

(f) Optional: ramp metering

Ramp metering is an effective way of breaking on-ramp vehicle platoons. If in situations where the upstream of an on-ramp is controlled with ramp metering instead of TLC, this control measure can replace TLC and be coordinated with the (d) cooperative merging strategy as well.

In light of the baseline simulation results in D3.1 (parameter set 'moderate') and the state-of-the-art of traffic management overview in Section 2,

Table 5 uses a rule-based decision making approach to suggest the 'best' traffic management control measure(s) in each cell, given the aforementioned traffic compositions (vehicle mixes), traffic demands (LOS A, B, and C) and the compliance rate assumptions.

Table 5: Types of traffic management measures to be taken depending on the traffic conditions.

Vehicle mix	LOS A	LOS B	LOS C
1	(a)	(b) + (e)	(b) + (c) + (e)
2	(a)	(b) + (e)	(b) + (c) + (e)
3	(a)	(b) + (c) + (e)	(c) + (d) + (e)

Note that this table is designed according to the simulation results of deliverable D3.1, which as we learn from simulation experiments, contains some non-optimal set-ups, such as the penetration rates of CVs and CAVs performing ToCs and MRMs, and the duration of MRMs when they occur. The proposed traffic management measures and their combinations in each cell are subjected to changes according to future updated results.

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

3.3.3.1 Recapitulation of the use case

For this use case, we need to satisfy the following functional constraints / dependencies:

- The TMC must be able to detect CAVs, CAV Platoons, and CVs speed, position, and direction in the merging section and up- and downstream.
- The TMC must be able to determine the traffic separation policy, which includes the preferred lanes for the different vehicle types for the different sections of the motorway(s).
- The TMC must be able to provide the traffic separation policy to CAVs, CVs and CAV Platoons.
- CAVs and CAV Platoons must be able to receive, process and execute the traffic separation policy and optionally support V2V manoeuvring coordination.
- CVs must be able to receive and convey the traffic separation policy to drivers.
- Time and space constraints must not limit the implementation of the traffic separation policy.

Spatial overview of the use case:

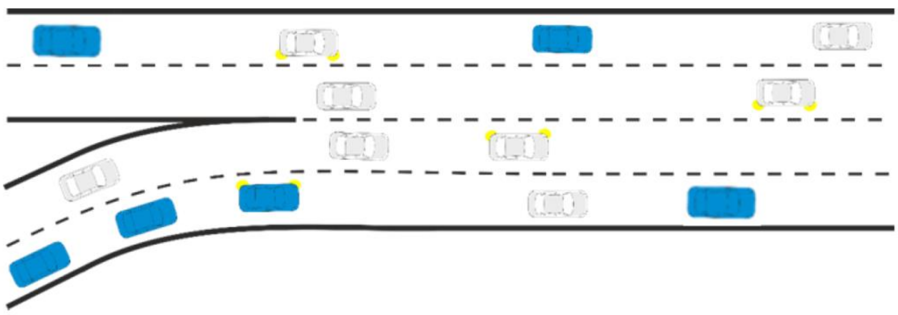

Figure 3.7: Schematic illustration of use case 3.1.

In deliverable D2.2 a timeline of actions was compiled to describe a traffic separation management scheme for mixed traffic at a motorway merge area aiming to prevent ToCs/MRMs. The core of this traffic management scheme lies in the provision of dynamic lane change advice to approaching vehicles (see also Figure 3.7), so that LVs (light-coloured vehicles) travel on the inner lanes while CAVs/CVS (dark-coloured vehicles) utilise the outer lanes. We expect that separating vehicles on dedicated lanes based on automation capabilities will minimise traffic complexity, and thus prevent ToCs/MRMs. The timeline of actions in D2.2 encompasses a higher level description of the proposed traffic management scheme (outlining the necessary steps required to prevent ToCs/MRMS in the proximity of the merge area). This Deliverable D4.1 however focuses on the identification of the conditions that warrant the activation of the traffic management policy. Moreover, it introduces the primary factors that are expected to play a significant role in the determination of the traffic separation area. At last, it summarises the required actions (advice to vehicles and corresponding manoeuvring) for the realisation of the traffic management policy, which will be elaborated in deliverable D4.2 when the simulation of the policy is discussed.

3.3.3.2 Context of the traffic measures

3.3.3.2.1 When to apply the traffic measures

Baseline simulation experiments conducted within the context of deliverable D3.1 indicated the impacts (on traffic, safety, and energy) of ToCs/MRMs at the merge area in the absence of traffic management. Thus, the conditions (traffic demand level, penetration rate of CAVs/CVs, and vehicle behaviour reflected by different parametrisation of driver models) under which ToCs/MRMs adversely impact traffic operations (on the road network examined in Scenario 3.1) were identified. This information is required to determine when traffic separation should be implemented (traffic conditions described by average speed, density, and traffic composition). According to the simulation findings in D3.1 traffic conditions in the proximity of the merge area (represented by the space-mean speed upstream of the merge area) significantly deteriorate in the following scenarios (see the red cells in Table 6):

- LOS C (irrespective of the vehicle mix and parametrisation scheme),
- LOS B and vehicle mix 3 (irrespective of parametrisation scheme)

Table 6: Baseline simulation scenarios (shown in red) that warrant the application of traffic separation according to prevailing traffic conditions upstream of the merge area for Service 3.1.

Vehicle mix	LOS A	LOS B	LOS C
1			(red)
2			(red)
3		(red)	(red)

However, it should be noted that traffic separation is not expected to be efficient when the percentage of CAVs/CVs is rather high or low in the vehicle mix. For example, in the case of LOS C and vehicle mix 1, 70% of the vehicles would be restricted to two out of four lanes; thus causing traffic to become too dense in these lanes and eventually break down. Therefore, future simulation experiments should also investigate the efficiency of the traffic separation as a function of the CAV/CV penetration rate.

Hence, average speed (as a congestion indicator) and traffic composition (as a feasibility indicator) in the proximity of the merge area should be monitored to determine when traffic separation should be imposed.

3.3.3.2.2 Where to apply the traffic measures

As highlighted in deliverable D2.2, the determination of the traffic separation area in the proximity of the merge section is required for the implementation of this management scheme. The traffic separation area dictates the location upstream of the merge section where vehicles are instructed to reach the advisable lane, and the location downstream of the merge area where vehicles are allowed to merge to their desired/target lanes. It is comprised of the following areas:

1. The lane change area where vehicles should implement the lane change advice
2. The ToC area where ToC is possible for CAVs that were unable to execute the advice
3. The MRM area where an MRM can be executed after an unsuccessful ToC
4. The downstream merge area where traffic flow is stabilised after merging and upward transitions can be instructed

Important parameters that affect the estimation of the traffic separation area are: (i) lane change duration, (ii) density, (iii) required left versus right lane changes, (iv) time until MRM, and (v) CAV deceleration capability during an MRM. A vehicle approaching the merge area travelling at, say 120 km/h (33,3 m/s) needs at least 150 m space to implement a lane change manoeuvre assuming an average lane change duration of 4.5 s (Toledo & Zohar, 2007). Since the lane change duration has been shown to increase with increasing traffic density, it is also important that the average density is measured upstream of the merge area. Moreover, it is known that the lane change duration is different between left and right lane changes. Thus, lane allocation of CAVs/CVs/LVs is expected to affect the spatial horizon of the traffic separation policy as well. Finally, the time until MRM and CAV deceleration capability during MRM will determine the required length of the ToC and MRM areas upstream of the merge location. The downstream merge area should be long enough to allow merging traffic streams to stabilise (speed harmonisation could be investigated as well) and CAVs to sense efficiently surrounding traffic (which might not be feasible in the merge location).

3.3.3.2.3 How to apply the traffic measure

Deliverable D2.2 outlined the actions from the vehicle side upon reception of the traffic separation policy. The actions varied based on vehicle type (automation and connectivity capabilities) and surrounding traffic. CAVs cooperation was also introduced as part of the traffic separation policy implementation. The latter aspects of the traffic separation policy were only briefly addressed in deliverable D2.2. A rigorous description regarding the exact implementation of the traffic separation policy will be provided in deliverable D4.2. The traffic separation policy can be also combined with Service 4 (Manage MRM by guidance to safe spot) when CAVs are forced to execute a ToC/MRM due to failure to reach the advisable lane by the TMC.

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

3.3.4.1 Recapitulation of the use case

For this use case, we need to satisfy the following functional constraints / dependencies:

- The TMC must be able to detect free safe spots, i.e. areas/lanes in front of the construction site for CAVs' temporary stay, and whether they are still available.
- The TMC must be able to provide information of the areas where automated driving is challenging to CAVs.
- The TMC must be able to distribute the position of the safe spot to the CAVs.
- CAVs and CVs need to be able to receive and understand the information.
- CAVs need to be capable of reaching the safe spot automatically.

Spatial overview of the use case:

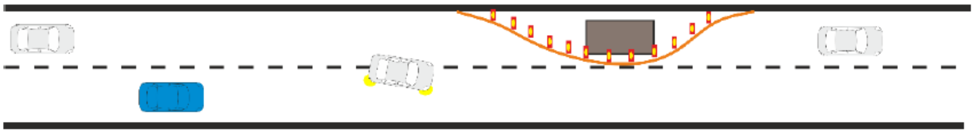

Figure 3.8: Schematic illustration of use case 4.2.

3.3.4.2 Context of the traffic measures

3.3.4.2.1 When to apply the traffic measures

The deployment of traffic management is warranted based on the prevailing traffic conditions upstream of the construction site. In deliverable D3.1 the effects of ToCs/MRMs upstream of the work zone were quantified in terms of the space-mean speed and average queue length. The latter performance measurements are indicators of congestion which can dictate the implementation of traffic management for specific traffic demand levels and vehicles mixes. Service 4 will be applied to both on an urban and motorway network.

Table 7 and Table 8 depict the simulation scenarios (characterised by different traffic demand levels and traffic mixes) when traffic management should be activated for the urban and motorway networks, respectively. In urban conditions, traffic management is required only for traffic demand corresponding to LOS C, while in motorway conditions congestion prevails upstream of the work zone in all simulated scenarios in D3.1. The reason why congestion emerges on the motorway network under any combination of the examined traffic demand levels and traffic mixes is twofold. Initially, the traffic flow rate corresponding to LOS A is higher for motorway lanes compared to urban lanes based on field evidence (as explained in deliverable D3.1, section 3.4). Secondly, vehicles travel faster on motorways due to the higher speed limits. Thus, lane changing and merging in the case of motorway conditions demand more space and are more complex, which in the end results in severe traffic turbulence upstream of the work zone (merge area). It also implies that traffic management actions need to begin much earlier than those in the current motorway scenario; this possibly requires us to spatially extend the network and start applying the traffic management measures far more upstream.

Table 7: Baseline simulation scenarios (shown in red) that warrant the application of traffic management measures (urban network) for Service 4.1.

Vehicle mix	LOS A	LOS B	LOS C
1			
2			
3			

Table 8: Baseline simulation scenarios (shown in red) that warrant the application of traffic management measures (motorway network) for Service 4.1.

Vehicle mix	LOS A	LOS B	LOS C
1			
2			
3			

3.3.4.2.2 Where to apply the traffic measures

The objective of Service 4 is to provide guidance to CAVs executing MRMs towards a safe spot (upstream of the closed lane) after an unsuccessful ToC. The TMC knows existing safe spots or can detect new ones (if needed and available), and uses a mechanism to reserve and allocate safe spots to upcoming CAVs that have activated an automation fall-back strategy and possibly finally need to execute an MRM. According to deliverable D2.2, a CAV that needs to trigger a ToC communicates to the TMC to reserve a safe spot in case of an MRM. Thus, the available space upstream of the work zone for traffic management is determined by a CAV's system limits and behaviour. If a CAV has to perform a lane change during the MRM to reach the safe spot, then the TMC can only support the lane change manoeuvre by coordinating actions with surrounding CAVs (if present). The TMC would need to monitor space-mean speed, density, and lane allocation of vehicles to support cooperative lane changing. However, if the TMC knows that the construction site area is challenging for a specific CAV (based on its automation capabilities), it can plan the management of the MRM to a safe spot in spatial and temporal terms. Therefore, the TMC should collect information about traffic conditions (average speed and density) and traffic composition (per lane) upstream of the work zone.

3.3.4.2.3 How to apply the traffic measures

Detailed information about the exact implementation of the aforementioned traffic management policy will be provided in D4.2 (encompassing the case when no safe spot is available), while cooperative vehicle manoeuvring will be thoroughly addressed in D3.2. However, note that we expect traffic management to differ between the urban and the motorway scenarios, due to different speed limits and examined traffic flow rates corresponding to different LOS. Moreover, it has to be stressed that traffic management might be rather demanding or even impossible in the cases that a ToC is decided and triggered by a CAV. This is the case when a CAV informs the TMC about an imminent ToC; if the CAV then decides the location of the TOR, then there might be limited space and time to do much when it comes to traffic management. Given its system limits, a CAV might issue a TOR very close to the work zone. Therefore, there might be limited space and time available to guide the CAV to the safe spot while also coordinating cooperative manoeuvring of surrounding CAVs. As traffic safety may become a specific concern here, we will address the issue further in deliverable D4.2 when the simulations are actually elaborated.

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

3.3.5.1 Recapitulation of the use case

For this use case, we need to satisfy the following functional constraints / dependencies:

- The TMC must be able to detect CAVs, CAV Platoons, and CVs speed, position, and direction along the road.
- The TMC must be able to determine the optimal position and moment for ToCs for each CAV.
- The TMC must be able to provide the ToC requests to CAVs and CAV Platoons.
- CAVs and CAV Platoons must be able to receive, process and execute the ToC requests.
- CVs must be able to receive ToC warnings from other vehicles and inform the driver.
- Time and space constraints must not limit the implementation of the ToC scheduling service.
- There must be enough time and space upstream of the no AD zone to apply the distribution of ToCs (and thus the ToCs themselves).

Spatial overview of the use case:

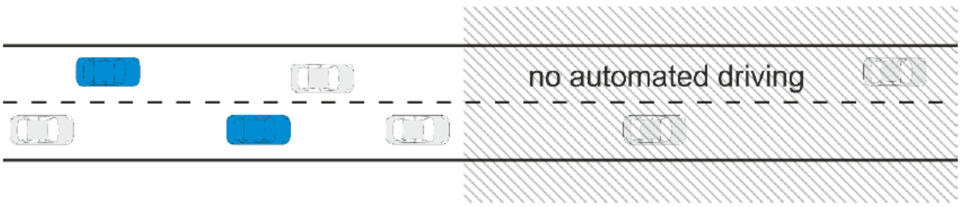

Figure 3.9: Schematic illustration of use case 5.1.

3.3.5.2 Context of the traffic measures

3.3.5.2.1 When to apply the traffic measures

The baseline simulations conducted in deliverable D3.1 did not show significant differences between vehicles mixes LOS A, B, or C. Due to the relatively conservative behaviour of the AVs for lane changes, results on speed and accepted distances did not imply major perturbations on traffic dynamics stemming from the transition processes, and consequently neither for safety, nor environmental indicators. This might shift significantly in presence of shorter headways for AVs. Such a situation may emerge either in case of more agile AV behaviour, or in the presence of automated platoons where AVs follow each other with reduced headways. Especially for the latter situation, we expect significant impacts resulting from the transition to manual control at an increased traffic density. Therefore we hypothesise that for LOS C and LOS B/vehicle mix 3 a distribution of ToCs may have major impacts on traffic dynamics and possibly on traffic safety as well.

Table 8: Baseline simulation scenarios (shown in red) that warrant the application of traffic management measures for Service 5.1.

Vehicle mix	LOS A	LOS B	LOS C
1			
2			
3			

3.3.5.2.2 Where to apply the traffic measures

As argued in deliverable D2.2, external reasons determine where a possible ‘no automated driving’ (NAD) zone might occur. As a minimal condition for the upstream distance d_{TOR} of a TOR to the NAD zone we require that the vehicle may come to a halt before the NAD zone, even if an MRM becomes necessary. To determine the minimal admissible distance, the distance corresponding to the ToC lead time and the necessary distance for a MRM, have to be summed up (see Figure 3.10). The latter distance would be initiated at the end of the ToC lead time if the driver remains irresponsive.

- The maximal lead distance d_1 may be estimated as the ToC lead time t_T multiplied with the vehicles’ estimated travelling speed v, where a slight overestimate (e.g., the maximal allowed speed plus 10%) may provide a safety margin.
- The distance required for an MRM at an initial speed of v is $d_2 = 0.5 \cdot v^2/b$, where b is the constant braking rate during an MRM, which we assume as $b_{MRM} = 3.0\ \mathrm{m/s^2}$ for the time being. Again a conservative estimate results from estimating a possibly lower value for b_{MRM}.
- Thus, the location for issuing TORs for this use case must lie further upstream or at distance $d_{TOR} = d_1 + d_2$ from the beginning of the NAD zone.

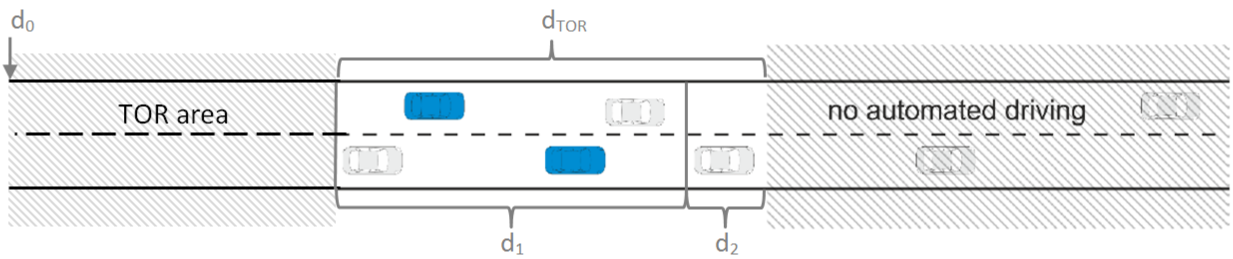

Figure 3.10: Schematic distribution area for TORs within a Transition Area.

3.3.5.2.3 How to apply the traffic measures

The simplest approach adhering to the principle of minimal (or latest) intervention would be to issue a TOR at distance d_{TOR} for all approaching CAV/CVs. However, in the case of dense traffic, and expected disturbances from ToC processes (e.g., platoon break-ups or heavily diminished driver performances) the spatial concentration or ToCs resulting from simultaneous TORs at distance d_{TOR}, might induce a concentrated perturbance within the area preceding the NAD zone. This may be ameliorated by distributing the TORs within a dedicated TOR area ranging from d_{TOR} farther upstream to a distance of $d_0 > d_{TOR}$, which may correspond to the maximal range of the RSU or to another threshold of efficacy for the TOR distribution, which may follow from the simulation studies envisioned in the TransAID project. Also, whether the distribution of perturbances will lead to an improved traffic flow at all is subject of investigations to be performed. The exact algorithm for scheduling and ordering of TORs, which is tested for the distributed approach, will be specified in deliverable D4.2.

3.4 Further approaches to integrated traffic management

Information regarding currently available traffic management procedures that include explicit interaction with and control of (connected/cooperative) autonomous vehicles is rather scarce. There do not exist many such overall implementations that take a more holistic approach, let alone that they have defined rules and systems that perform traffic management in an integrated way comprising local control and higher levels of vehicle autonomy. We already elaborated on a few of these in Section 2.2, of which the simulation with VANETs seemed the most promising one that bridges local control of intersections with AVs and/or was able to monitor a road stretch with consecutively placed sensors and communicating congestion information wirelessly to the AVs. The rest of our discussion centres around the available and known approaches for traffic management that considers vehicle autonomy, as well as vehicles themselves acting as sensors which have the benefit of cooperative sensing to upscale the potential for traffic management. Note that in our subsequent discussions we do not make a strict distinction between the various levels, i.e. strategical/tactical (from a policy maker's point of view), operational (from a traffic manager's point of view), and technical (from an ICT point of view), as this is in many cases explicitly implied from the descriptions.

Looking at traffic management in the Horizon 2020 MAVEN project, we see how interactions on longer stretches of road are taken into account, whereby (C)AVs encounter a multitude of situations, as shown in the illustration in Figure 3.11.

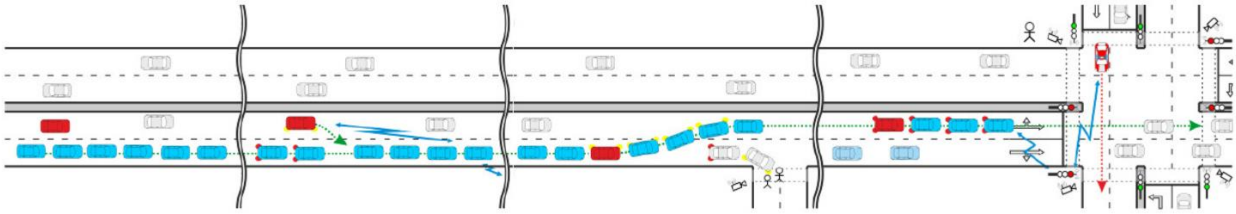

Figure 3.11: Illustration of the different types of interactions within the Horizon 2020 MAVEN project.

On a high level the traffic management system considers measures such as traffic light controls, queue length estimation, green waves, and platoon management (forming, joining, leaving, and breaking). On a lower level, the traffic control mechanism uses information sent from the vehicles to the infrastructure (i.e. planned routes, desired speeds, platoon sizes, time and space headways, …), and vice versa with speed and lane advices communicated from the infrastructure back to the vehicles. In addition, there is a feedback mechanism included so the infrastructure can know which vehicles complied with its advice. The traffic management infrastructure estimates queue lengths and calculates an advised lane speed based on these, as well as providing vehicles with lane suggestions at intersections (amongst others, the target lane and distance to the stop line). Note that all the sent information is packaged in containers that are backward compatible extensions of CAM messages (Day 1). For platooning, the system adopts a mix between a distributed and a centralised approach. Here, vehicles perform most of the platoon management among themselves in a cooperative way, but the platoon leader has to communicate the characteristics of the platoon to the infrastructure. LVs and vulnerable road users (VRU) are included via collective perception and classic road-side detection techniques (e.g., cameras and inductive loop detectors). They are however not addressed via conventional techniques such as VMSs, but rather indirectly by adapting CAVs' paths. Considering MAVEN's system description, the TMC takes on the role to service traditional traffic management functions, complemented with network optimisation, and honouring road authorities' policy parameters.

Modern-day traffic management also centres on urban environments, becoming a part of the so-called smart cities. Here, traffic management is also seen as using a GIS-enabled digital road map of a city coupled to the power of analytics to smoothen traffic flows. Mostly this management comes in the form of advice relayed to an individual road user, which typically takes the form of routing advice, departure time, congestion-ahead warnings, or parking information. Most smart traffic management platforms aggregate all kinds of information in a centralised way, apply traffic flow modelling and prediction to this in order to estimate the state of the network at current and future time instances. This is then used to drive the controls for, e.g., traffic lights, or in some cases to relay routing information to individual vehicles. And by leveraging the upcoming Internet of Things (IoT), traffic management finds new ways with decentralised approaches to optimise traffic in the road network, and (local) intelligent algorithms to manage all traffic situations more accurately. For example, traffic is monitored with road-side units, and the density is estimated. IoT (through RFIDs) can be used to prioritise emergency vehicles and the like. All this is then used to predict traffic density ahead of time, and controlling traffic lights at intersections. The backbone of such systems adopt social, mobile, and cloud (SoMoClo) platform technologies. Typical uses include traffic management solutions as high-occupancy vehicle (HOV) lanes, autonomous road inspection systems, electrical vehicle sharing, smart (valet) parking, real-time and predictive route guidance, … In this respect, the CIMEC Horizon 2020 project specifically addressed the insights and needs of local city authorities, understanding their views and requirements on C-ITS applications.

On the other end of the spectrum we have the previous FP7 project i-GAME which had the goal to develop technologies that speed-up the real-life implementation of automated driving, taking V2X communication explicitly into account. Their approach relies on measures such as vehicle platoon management, speed adaptation at traffic lights, vehicle merging, … The main difference with some of the current approaches is that i-GAME adopted a supervisory control, providing both event-driven control to initiate vehicle manoeuvres and real-time control to execute the manoeuvres. This stands in contrast to TransAID, whereby the traffic management system relies in part on the local self-organising interactions of connected vehicles (e.g., during cooperative sensing and manoeuvring).

A noteworthy mention is the TRAMAN21 FP7 project, which considers traffic management for the 21st century. Its main objective is to develop the foundations and first steps that will pave the way towards a new era of future motorway traffic management research and practice. They are explicitly looking at the relevance of (C)AVs for improved traffic flow, and develop specific options for a sensible upgrade of the traffic conditions, particularly at the network's weak points, i.e. at bottlenecks and incident locations. Most of the work in the TRAMAN21 project is focused at developing new traffic flow modelling techniques, and defining new control approaches.

Considering traffic management at a more concrete setting, we note the work at the time of writing being done in the Horizon 2020 interACT project. There they have described a scenario ontology (created offline) that contains (i) a taxonomy of classes and subclasses, (ii) properties and relations for all these (sub)classes, and (iii) a set of rules that govern their behaviour and control. All this information comes together in a rule engine that does real-time scenario recognition, in order to determine in which kind of 'scenario' an AV is situated. This approach has the advantage that the rules can easily be updated or new ones be added, albeit at the cost of a slightly higher computational complexity.

Furthermore, a recent project (SOCRATES 2.0) will tackle the cooperation between road authorities, service providers, and car manufacturers (providing an approach not unlike TransAID which acts as an intermediary service, see also Section 3.2.1). Their focus lies on developing the standards for the future of road mobility, connecting traffic information, and unique public-private cooperation on a pan-European scale. They boast a fully-interactive traffic management system, consisting of supporting people on their travel from an origin to a destination (as opposed to just managing and influencing traffic) and providing services for road users (e.g., smart routing, actual speed and lane advice, local real-time information, hazard warnings, …).

Finally, let us note the work being done in the Horizon 2020 INFRAMIX project, which adopts nomenclature similar to TransAID's, i.e. scenarios and use cases per scenario. Their focus lies on dynamic lane assignment (including speed recommendations), construction sites and roadworks zones (with single lane closure as well as new lane design), and bottlenecks. For this, they assume differing penetration rates of automated vehicles, consider exceptional traffic situations (e.g., adverse weather conditions), specific circumstances in which, e.g., an LV drives on a dedicated lane for automated vehicles, and lane advice at bottlenecks to control the traffic's throughput. Within the context of dynamic lane assignments, INFRAMIX considers dedicated lanes for AVs that can be allocated to either AV passenger cars or trucks based on the time of day and prevailing traffic conditions. In case of work zones, all types of vehicles are informed about the downstream construction site, but there is no specification yet as to how this is exactly done. So the work related to traffic management procedures and protocols is also not (fully) worked out in this case. Note though that their approach to vehicle classification is slightly different than the one adopted in TransAID: INFRAMIX considers conventional vehicles (SAE 0, 1, or 2), connected conventional vehicles (SAE 0, 1, or 2 with 5G or G5 communication capabilities), and automated vehicles (SAE 3, 4, or 5). Similar as in TransAID though, INFRAMIX adopts an integrated simulation platform, comprised of VSimRTI, ICOS, SUMO, OMNET, and other – to be developed – modules (similar to TransAID's applications). As their work regarding traffic management, traffic state estimation, and traffic sensing is still ongoing, discussions and interactions with the INFRAMIX project will prove to be beneficial for the TransAID project.

4 General communications requirements for traffic management systems

The implementation of the Services designed in the TransAID project requires the collection of information about the traffic stream. It is necessary to collect information about the traffic composition and about the position and dynamics of the vehicles on the road. This information is locally gathered by the RSUs from their own sensors (e.g., cameras), from sensors installed in the road (e.g., inductive loop detectors), and from the CVs and CAVs through collective perception (which increases the reliability of the information that is external to a vehicle). The CAVs and CVs can send information about themselves, but also information about other vehicles or detected obstacles. Similarly, the RSU will send information about detected vehicles and obstacles to CVs and CAVs in order to enlarge their environmental perception. This information needs to be transmitted periodically in order for all relevant actors to always be aware of the traffic conditions.

After the collection of information, the next step of the TransAID services will be the definition of the specific traffic measures to be applied. These traffic measures need to be disseminated to the traffic stream along with information about the environment necessary for the applications of the traffic management rules (e.g., information about road works, speed limits, map of the road, …). This can be done by employing V2X communication for communication with CVs and CAVs, and by employing other types of conventional signalling (i.e. via VMS) for the communication with LVs and AVs. This information will be transmitted once the vehicles are approaching the TA, under the assumption that there is enough time to allow them to execute the required manoeuvres. It is also possible to enrich (existing) road traffic signs with (standardised or pre-agreed upon) digital information (e.g., bar- or QR-codes), such that (C)AVs are able to interpret these more efficiently and unambiguously.

Additionally, some Services require the coordination of cooperative manoeuvres for CAVs. The coordination of manoeuvres can be done both locally by the coordination between the affected vehicles, and they can even be assisted by the infrastructure taking advantage of its inherently larger perception of the environmental scope. In order to allow the coordination between vehicles it is necessary that they periodically transmit their future trajectories, so that other vehicles can compare their own trajectories with the received ones and predict potential problematic situations that can be avoided through cooperative manoeuvring.

> Note however that the latter is a highly time critical issue. Automated vehicles plan a spacious set of trajectories within milliseconds for the next discrete time frame to determine their next step. From an automation point of view it might be nearly impossible to transmit one certain trajectory (for a larger time frame of seconds) with a confidence level high enough so that other vehicles can take it into account. This by itself poses some technical challenges. Within TransAID, we intend for vehicles to send trajectories and the RSUs to send (rough) target lane/speed/… advices, all via manoeuvre coordination messages (MCM). At the moment, it remains an open question as to where this is done in the simulation. TransAID's idea is to first implement cooperative manoeuvring between vehicles (either in SUMO or via interaction with the application layer through the iCS), secondly to involve traffic management advices, and only thirdly to assume more realistic communications by involving NS-3.

Regarding the communication requirements, Table 9 gives an overview of them coupled to the type of communication, the type of V2X message, and the periodicity of transmission.

Table 9: Communications requirements

Requirement	Type of communication	V2X message	Type of transmission
Gathering of information about the traffic participants	V2V, V2I, I2V	CAM	Periodic
Gathering of information about the detected vehicles on the road	V2V, V2I, I2V	CPM	Periodic
Dissemination of a map of the road to the vehicles	I2V	MAPEM	Non-periodic
Dissemination of traffic signs of the road to the vehicles	I2V	IVIM	Non-periodic
Dissemination of alerts for environmental incidents impacting the traffic	I2V, V2V, V2I	DENM	Non-periodic
Coordination of manoeuvres between CAVs and/or the infrastructure	I2V, V2V	MCM/LAM	Periodic

Considering these communication requirements, we thus make a distinction between communications among vehicles (V2V) on the one hand and between vehicle and infrastructure (V2I and I2V) on the other hand. The specific type of message transmitted can be a cooperative awareness message (CAM), a collective perception message (CPM), a MAP (topology) extended message (MAPEM), an infrastructure-to-vehicle information message (IVIM), a decentralised environmental notification message (DENM), or a manoeuvre coordination message (MCM) coupled with a logical acknowledgement message (LAM). Specific information regarding each of these message types, as well as specific communication requirements, can be found in deliverable D5.1 (Definition of V2X message sets).

As we progress further towards simulation of traffic control messages within the integrated simulation platform, we will also need to understand for each traffic control measure the type of information that needs to be collected, from which vehicles (and at which distances) this needs to happen, and information regarding the latency and reliability in order to tune the messaging.

> Note that in TransAID's first iteration we assume perfect and clear communications, irrespective of available bandwidths et cetera (the real-world situation is described in WP5 and simulated in WP6). However, we should keep in mind that latency plays an important role. For example, a vehicle travelling at 120 km/h travels correspondingly at 33 m/s. This means that within six seconds, the vehicle has crossed a section of 200 m long. That assumes that any gathering of information, transmitting it to the relevant RSU and ultimately TMC, formulating of the correct advice, and implementing the request control action, all has to take place within this short time frame. If not, then the information is useless as there will not be enough time to 'react' appropriately to the traffic conditions.

5 Conclusions

This deliverable D4.1 started with an outline of the state-of-the-art of traffic management. The focus first laid on general approaches whereby the underlying principle is not to just look at single locations, but rather to use the entire network to distribute traffic more wisely and as such postpone or even prevent the formation of congestion. Some promising techniques in this respect are coordinated network-wide traffic management (including regional traffic management), using key performance indicators to make the entire process performance-based and more cost effective, hierarchical controls that are implemented via layered architectures (spanning the range from top-down regulation over self-organisation to full bottom-up regulation), and Traffic Management as a Service. Next, we looked at the trend towards more cooperative systems which is well-suited for enhanced traffic management. This makes the systems smarter, in that – as opposed to the classic approach whereby large groups of road users are targeted – we can now target vehicles individually at a sufficient level of penetration of cooperative vehicles. Going even further, the collaborative approach for automated vehicles is also a direction in which future traffic management systems are evolving. Finally, we looked at the expected impacts that machine learning techniques and artificial intelligence in general would have on traffic management. These are currently typically encountered in traffic light control and congestion / queue length predictions. There remains however a large theory-practice gap whereby only limited advancements are exploited in the field and artificial intelligence is currently mostly used as a building block. After surveying the state-of-the-art of traffic management, we came to the conclusion that there are quasi no (readily available) implementations of more advanced and/or generalised traffic management schemes that take higher degrees of vehicle automation into account. Most current research on this topic focuses on various aspects, such as solving partial problems/bottlenecks with specific measures (e.g., a new type of adaptive cruise-control, intersection management, a different kind of traffic light optimisation, creation of vehicle platoons, wireless communication to the driver/vehicle, …) and providing insight for the potential of autonomous vehicles in traffic management. In itself, all these solutions are very fine and usable; however, there are no experiments / setups whereby these solutions have to come together to provide an answer to traffic management on a higher level, allowing the interplay between all the various solutions to lead to a better system performance. This is where TransAID can make the difference.

The bulk of the work in this deliverable then focused on the traffic management procedures and protocols that we will adopt within TransAID. In first instance, we linked traffic management to the concepts of goals, policies, and strategies. Then, we considered traffic management from an EC perspective with special emphasis on the C-ITS platform, ITS Action Plans, and Sustainable Urban Mobility Plans. Within this context, we formulated TransAID's outline of the traffic management framework. Here we positioned TransAID as an intermediary service provider, acting as a trusted (and possibly mandated) third party. Within this framework, TransAID makes a distinction between road-side units and the traffic management centre and how they are going to interact with each other. Leveraging the capabilities of connected vehicles, we also explained the high- and low-level traffic management operations. Interestingly, this may lead to the road-side communicating some advice to the vehicles which may seem counterintuitive, even breaking the law in some cases. This raises various discussions on the compliance of automated vehicles to traffic laws, a point that is to be further investigated.

The work done for TransAID's traffic management then naturally builds up to a more in-depth discussion of the five selected services and use cases, each time highlighting when, where, and how traffic measures should be applied. The idea is that these recipes are given from the point of view of a traffic management centre, which will lead to the timelines described in deliverable D2.2 (which are mostly viewed from the context of the vehicles themselves). This will then also automatically take into account the time scales of events occurring to which a traffic management system must react and the expected response times of drivers are investigated.

After explaining some further approaches to integrated traffic management, paying special attention to the inclusion of CAVs in the loop, the document concludes with several general communications requirements for traffic management systems, focusing on the types of messages and their periodicity. This will prove to be invaluable when considering, e.g., collective perception by CAVs, and how this can be tied into a more modernised version of traffic management.

The topics discussed in this deliverable will form direct input into deliverable D4.2, where we will provide both simulation code and descriptions of the simulation setup and execution (based on the use cases discussed in the current deliverable D4.1), as well as the assessment of the various use cases (via the safety and efficiency indicators) with respect to traffic management of automated driving at Transition Areas.

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7 Appendix A: SAE levels of autonomy

The Society of Automotive Engineers (SAE) defined the following levels of autonomy, according to the new SAE international standard J3016[6]:

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Key definitions:

- **Dynamic driving task** includes the operational (steering, braking, accelerating, monitoring the vehicle and roadway) and tactical (responding to events, determining when to change lanes, turn, use signals, etc.) aspects of the driving task, but not the strategic (determining destinations and waypoints) aspect of the driving task.
- **Driving mode** is a type of driving scenario with characteristic dynamic driving task requirements (e.g., expressway merging, high speed cruising, low speed traffic jam, closed-campus operations, etc.).
- **Request to intervene** is notification by the automated driving system to a human driver that s/he should promptly begin or resume performance of the dynamic driving task.

[6] Information reproduced from https://www.sae.org/misc/pdfs/automated_driving.pdf

8 Appendix B: Day 1 and Day 1.5 C-ITS services

Note: information taken from EC (2016).

8.1 Day 1 C-ITS services

- Hazardous location notifications:
  - Slow or stationary vehicle(s) & traffic ahead warning
  - Road works warning
  - Weather conditions
  - Emergency brake light
  - Emergency vehicle approaching
- Other hazards:
  - Signage applications
  - In-vehicle signage
  - In-vehicle speed limits
  - Signal violation / intersection safety
  - Traffic signal priority request by designated vehicles
  - Green light optimal speed advisory
  - Probe vehicle data
  - Shockwave damping (falls under European Telecommunication Standards Institute (ETSI) category ‘local hazard warning’)

8.2 Day 1.5 C-ITS services

- Information on fuelling & charging stations for alternative fuel vehicles
- Vulnerable road user protection
- On street parking management & information
- Off street parking information
- Park & ride information
- Connected & cooperative navigation into and out of the city (first and last mile, parking, route advice, coordinated traffic lights)
- Traffic information & smart routing

9 Appendix C: Used traffic conditions and vehicle mixes

The ‘right’ traffic management measures are dependent on traffic conditions and the vehicle mix, as defined in deliverable D2.2 and updated in D3.1. The following tables were reproduced from those deliverables for reasons of clarity and completeness:

- Definition of the levels of service (LOS) A through C
- 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 during 1st project iteration

Table 10: 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 11: Distribution of passenger vehicles, light and heavy goods vehicles

Vehicle type	**Share**
Passenger vehicle	85%
LGV	5%
HGV	10%

Table 3. 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 4. 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%	-	-