Traffic Management for Connected and Automated Driving (TM4CAD)

Recommendations for the dialogue between NRAs and automated vehicles developers

Deliverable D5.1 Version 2.0 (final version)

March 2023

This project is funded by CEDR Call 2020 Impact of CAD on Safe Smart Roads.

Consortium partners: MAP traffic management (the Netherlands), Traficon (Finland), Transport & Mobility Leuven (Belgium), WMG, University of Warwick (United Kingdom), Steven Shladover (independent consultant), and Keio University (Japan).

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Executive summary

The project TM4CAD (Traffic Management for Connected Automated Driving) was selected in CEDR Transnational Road Research Programme Call 2020 for funding with regard to call topic C Traffic management. The project commenced its activities on 13 September 2020 and was completed 18 months later.

This deliverable (D5.1) provides a complete set of realistically implementable requirements from traffic management systems and road operators to CAD systems and automated vehicle manufacturers. This was done by means of on-going collection of requirements, first from a technical point of view (for traffic management and CAD systems), and then highlighting the roles that both the road operators and traffic management centres and vehicle manufacturers (and Tier-1 providers, ADS developers, AV fleet managers/operators) play in this respect.

Most of the requirements were given at a higher level, based on the work done in WP2, WP3, and WP4, with extra inputs stemming from the MANTRA, EU EIP, and TransAID projects.

In addition, we focused on how to best convey them to the relevant stakeholders. To this end, we held open stakeholder dialogues through workshops. We recommend next to publish the requirements in specific (standardisation) bodies on the one hand, and to establish a so-called codified highway code which has the ability to integrate all requirements in the long term (see also Appendix A).

The output of WP5 was validated in TM4CAD's workshop in November 2022, for an international audience including researchers, road operators, and vehicle manufacturers, presenting:

- The use cases that were specified in WP4
- Requirements to AV manufacturers
- An infrastructure evolution path
- An overview of how the codified highway code works

➔ The workshop's aim was to pave the way to a more unified and cooperative roadmap.

Regarding the question "*Should NRAs set requirements on the desired behaviour of (partly) automated vehicles on where and how they should drive?*". The answer is nuanced: the desired behaviour of (partly) automated vehicles should be defined as a product of the interactions between the NRAs and the developers of the vehicle technology to produce a balance between technological feasibility and serving transportation system needs. So in practice this entails much more interaction between NRAs on the one hand and ADS developers on the other hand. Prime examples of such discussion items in which it makes sense for NRAs to be engaged as well are the definition of an MRM, what constitutes an MRC, what behaviour is expected from an automated vehicle or ADS (automated driving system), and what are the consequences of any road code requirements and decisions taken by an ADS?

There currently exists a large gap of information between both parties in the spectrum: NRAs do need to understand how an ADS will react under certain conditions, and OEMs need to understand what is expected by the NRAs in order to finetune their ADS' behaviours. In order to mitigate this, we recommend a mutual exchange of information in an open dialogue.

Finally, A vision for these requirements will typically be created from a perspective of vehicle safety. Safety for the vehicle, for the passenger, and for the environment (i.e., the other traffic participants). Based on a common understanding of the stakes involved, both NRAs and ADS developers can work together, and define what is realistically possible.

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1 Acronyms and abbreviations

Acronym	Definition
ADS	Automated Driving System
AV	Automated Vehicle
CAD	Connected and Automated Driving
CAM	Cooperative Awareness Message
CAV	Connected Automated Vehicle
CCAM	Cooperative Connected Automated Mobility
CEDR	Conference of European Directors of Roads
CEF	Connecting Europe Facility
C-ITS	Cooperative Intelligent Transport Systems
C-V2X	Cellular Vehicle-to-Everything (communication)
DG	Directorate General
DOVA	Distributed ODD attribute Value Awareness
DoRN	Description of Research Needs
EC	European Commission
ECU	Engine control unit
ER	Essential result
EU EIP	EU ITS Platform
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HD	High definition
HMI	Human Machine Interface
I2V	Infrastructure-to-Vehicle (communication)
ICT	Information and Communication Technology
ISAD	Infrastructure Support for Automated Driving
ISO	International Standardisation Organisation
ITS	Intelligent Transport Systems
L3	Level 3 (driving automation)
L4	Level 4 (driving automation)
MRC	Minimal-Risk Condition
MRM	Minimal-Risk Manoeuvre
NRA	National Road Authority
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
OR	Operational result
PEB	Programme Executive Board
RQ	Research Question
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SRTI	Safety-related traffic information (Directive)
TM4CAD	Traffic Management for Connected and Automated Driving
TMC	Traffic Management Centre
TMS	Traffic management system
ToC	Transfer of Control
UN	United Nations
UNECE	United Nations Economic Commission for Europe
V2I	Vehicle-to-Infrastructure (communication)

Acronym	Definition
V2X	Vehicle-to-Everything (communication)
WP	Work-package

2 Introduction

2.1 TM4CAD

TM4CAD explored the role of infrastructure systems in creating ODD (Operational Design Domain) attribute value awareness for Connected and Automated Driving (CAD) systems. The Distributed ODD attribute Value Awareness (as a state of the ADS) means that the ODD attributes' values known to the ADS are obtained through a combination of on-board and off-board sensors/sources. As a starting point we proposed various approaches for providing distributed ODD attribute value information and defined acquisition principles of the information based on exchange among the stakeholders, ultimately to enable CAD systems to be aware of their ODD in real-time. Moreover, TM4CAD has demonstrated the basic mechanisms of ODD management via two real-world use cases, which build on the premise of interaction between traffic management systems and CAD vehicles. This provides NRAs and other traffic managers insight into methods to inform CAD systems about the kinds of support they can provide for CAD operations on European roads.

To gain a complete understanding of traffic management for CAD, the TM4CAD project:

- Identified the full range of ODD attributes for consideration, based on experience from working on ODD issues in standardization activities and in other related research projects;
- Integrated the very different perspectives of the CAD vehicle system developers and the road authorities and operators to focus on the overlapping areas;
- Introduced the concept of ODD attribute value awareness and the role of infrastructure in it;
- Developed recommendations based on the technical constraints of the ODD-relevant information that can be perceived and exchanged in real time by the NRAs and the sensing systems of the CAD-equipped vehicles;
- Provided insights on how to support CAD operation and ODD management, and how ISAD should be refined for traffic management use, and
- Detailed how traffic management systems and CAD vehicles can best interact to improve traffic operations.

The project was conducted by a consortium led by MAP traffic management (MAPtm) from the Netherlands. The other members of the consortium are Traficon (TRA, Finland), Transport & Mobility Leuven (TML, Belgium), WMG, University of Warwick (UoW, United Kingdom), Steven Shladover (independent consultant), and Hironao Kawashima (Keio University, Japan).

Project participants left to right, top: Sven Maerivoet (TML), Risto Kulmala (TRA), Steven Shladover, Ilkka Kotilainen (TRA); bottom: Jaap Vreeswijk (MAPtm), Siddartha Khastgir (WMG, UoW), and Anton Wijbenga (MAPtm). Not in the photo: Hironao Kawashima (Keio University) and Tom Alkim (MAPtm).

2.2 Objectives and target audience

The main objective of this deliverable was to provide a complete set of realistically implementable requirements, from traffic management systems and road operators, to CAD systems and automated vehicle manufacturers. In addition, it presents an evaluation of the most effective ways to document and publish them. As a solution, TM4CAD focuses on codifying the requirements digitally (pertaining to desired behaviour) into a so-called codified highway code. To enable the road operators to define *good behaviour* for CAD systems, the next step was the introduction of a novel ODD and ISAD based highway code concept, along with a common set of ODD attributes (in similar spirit as to how a *regular* highway code defines the expected behaviour from human drivers). This will enable manufacturers and road operators to communicate in a common language and allow for changes in CAD traffic throughput due to ODD and ISAD changes. This method is already being pushed forward within the UK, based on road authorities' and manufacturers' needs and interests. Simultaneously, this code will encompass expected behaviour in certain operating environments, therefore providing a close link with the ODDs and ISAD levels.

The target audience is the CEDR Programme Executive Board (PEB) coordinating the CEDR 2020 research call and the larger body of NRAs that they represent. In addition, this deliverable also addresses the ADS developers to some extent.

2.3 Research questions and expected outcomes/outputs

The following Research Questions (RQ), Essential Results (ER) and Operational Results (OR) from the larger list addressed by TM4CAD are tackled by this deliverable (D5.1):

***Table 1:** Mapping of Research Questions and Expected Results to Deliverable 5.1*

Research question / result	Addressed in paragraph(s)
RQ1: Should NRAs set requirements on the desired behaviour of (partly) automated vehicles on where and how they should drive?	Section 3.2
ER3: Determination of the information needs and who is to provide this information in the bidirectional interaction between TMC and vehicle	Sections 3.1, 0, and 4
OR3: A vision on what requirements an NRA should set on the desired behaviour of (partly) automated vehicles, where and how they should drive	Sections 3.2 and 4
OR4: As OEMs are publishing their requirements towards road design, establish what are the requirements from NRAs towards vehicles (e.g., on concepts like minimal risk manoeuvre / hand over request) from a safety perspective?	Sections 3.2 and 4

2.4 Relationship with other work packages

WP5 did not add new research and development activities to those undertaken by WP2, WP3, and WP4 (see also Figure 1). Instead, it exploited the results of these work packages as well as the workshops they organised. The task of WP5 was to derive, collect, and consolidate requirements to CAD systems and the automated vehicle industry, while assessing effective ways to document and publish these requirements (e.g., through UNECE or a highway code). In this manner, WP5 added to the work of the other WPs.

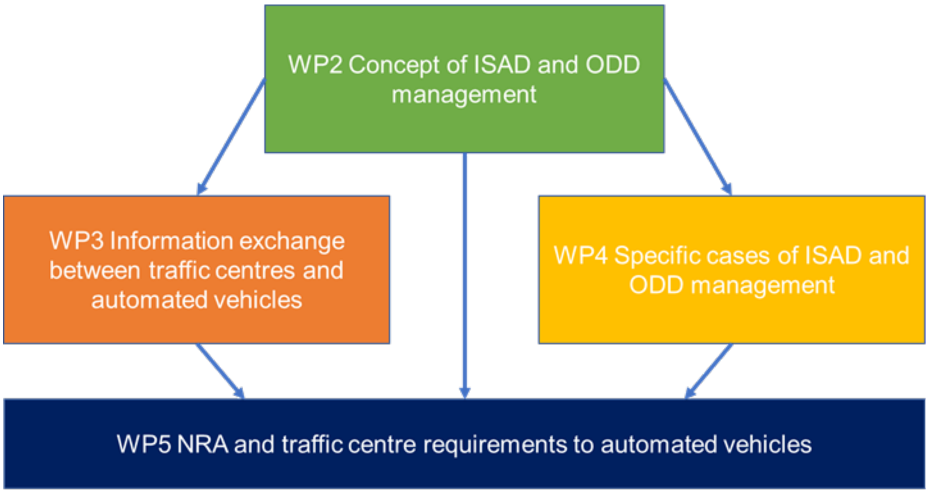

Figure 1: *Relationship of WP5 (and D5.1) with other work packages of TM4CAD.*

2.5 Structure of the document

This report starts with an on-going collection of requirements in Section 3, first from a technical point of view (relating to existing requirements and those identified within TM4CAD), and then highlighting the roles both the national road authorities (and traffic management centres) and vehicle manufacturers (and Tier-1 providers) play in this respect. Then, Section 0 presents some critical remarks and recommendations based on the previous findings. Finally, Section 4 summarises our conclusions at providing an answer to research question 4, i.e. whether or not road operators should set requirements on the desired behaviour of (partly) automated vehicles on where and how they should drive. In Appendix A we present our proposal for a codified highway code to best convey the requirements set out in this document.

3 Requirements identification

In this section we collect the various requirements that are relevant for road operators in light of desired competencies and behaviour of automated vehicles. These requirements entail two views: on the one hand there is, e.g., the information that needs to be provided by automated driving systems (ADS), whereas on the other hand the point of view lies more on the information that ADS need to be able to receive and act on.

In the next sections we first focus on existing requirements from previous project such as MANTRA and EU EIP. Thereafter we list new requirements, based on TM4CAD findings. Note that these requirements implicitly take the desired behaviour of (partly) automated vehicles (including where and how they should drive) into account, while also considering the safety perspective (cf. minimal risk manoeuvres, system disengagements, and handover requests).

Finally, we highlight the roles that both national road authorities and vehicle manufacturers (and Tier-1 providers) play in this respect.

Note that for requirements related to the quality of data provisioning, we refer to Section 4 in TM4CAD's Deliverable D3.1 (Kulmala et al., 2023).

3.1 Existing requirements

The MANTRA project of CEDR and CEF-supported EU EIP project identified a number of previously suggested requirements towards ADS developers and CADs (MANTRA, 2020 and EU EIP, 2020). They are as follows.

- In order to reduce the increased road pavement rutting and wear, the ADS providers should ensure **wheel path alteration** in cross-section especially by heavy vehicles closely following each other.

- Concerning HD maps and keeping them updated at all times the fleet managers and ADS developers should **provide feedback on HD maps** and report any anomalies in their content.

- The AVs should provide information on incidents, e.g., by detecting stopped vehicles and roadway defects, and provide relevant incident and event related data to traffic managers as well as service providers.

- The AVs could also be used to **monitor the performance of road works management**, i.e., the impact on the traffic stream, local traffic safety, communication of the local conditions, etc.

- New approaches need to be developed for **road condition data collection** for deterioration monitoring in cooperation with ADS developers and CADs.

- The automated vehicles should give **external indication** of being driven by ADS or being last in platoon, to ensure safe and efficient traffic management; this way, other human drivers can take the (seemingly) different behaviour of the ADS into account.

- ADS developers, fleet managers and CADs need to **acknowledge the conductor role** of road authority/ operator in traffic management (as in incident management) and see to it that the AVs act accordingly.

- The ADS developers and CADs need to consider **harmonising the pictograms and message content** used by road operators and vehicles. In the future, the road users (drivers, automated vehicles, and vulnerable road users) will receive information in addition to roadside variable and dynamic message signs also via their onboard devices. For the safety of the road users, it would be good to harmonise at least the pictograms used by the different stakeholders, but preferably the whole message content.

- There is a need to develop and use **standardised communication protocols** with TMC, fleet managers, service providers, and automated vehicles.

- The safe behaviour of highly automated vehicles at the end of their ODD needs a standardised solution for the minimal-risk manoeuvre, likely specific ones for different road and traffic environments. Road operators should be a key stakeholder in such standardisation actions. An example is slowing down and proceeding at a low speed to a large parking area beside the next exit as **a workable MRM solution** to be adopted by CAD developers.

- The AVs must supply **information on ODD termination risks and of any MRMs** conducted with sufficient detail and location accuracy. This is essential for the safe and efficient traffic management of the road network.

- The fleet managers need to set up and operate **fleet supervision centres** for their automated vehicles. Some national road authorities and many road operators deal with the operational maintenance and winter maintenance of their road networks. Thereby, those road authorities and operations need to set up their fleet supervision centres for automated maintenance vehicles.

- Standardisation actions need to be pursued concerning the marking and management of incident and road works sites taking into account the capabilities of and requirements towards highly automated vehicles. The **compliance to such standards** should preferably be mandated, at least on the European level. The leading or coordinating role of road authorities and operators in road incident management needs to be specifically mandated, preferably on the European level.

3.2 New requirements derived from TM4CAD findings

3.2.1 First set of requirements to be satisfied by ADS

The first set of requirements highlighted in TM4CAD mainly relate to the information that needs to be provided by automated driving systems (ADS), i.e.:

- ADS must have a clearly defined ODD, using a common set of ODD attributes.
- ADS must actively monitor the status of ODD attributes critical to safe operation.
- ADS must cease automated driving if ODD constraints are violated.
- ADS must be able to act on prescriptive traffic management measures set by road operators.
- ADS must behave in line with predefined rules of the road.
- ADS should be able to act on advisory traffic management measures set by road operators.
- ADS must cease automated driving if it cannot comply to the rules of the road.
- ADS must announce to traffic centres when and where they initiate an MRM.
- ADS should let the road operators and traffic management centres know the reason behind an MRM especially if the reason is due to a factor affected by the actions of the road operator and traffic management centre.
- ADS should let road operators and traffic management centres know whether the vehicle is being operated by the ADS, as this might prove useful in case a traffic management measure requires a different approach for dealing with (highly-) automated vehicles.

From our workshops we also noted the following observations which are also relevant in light of the different roles and responsibilities that we discuss further on:

- There is still some lack of clarity with respect to e.g., the expectations from digital twins, who hosts/manages them, high-definition maps, and all related message protocols (MAPEM/SPATEM).
    - The Car2Car consortium, as well as the AdaptIVe project contain protocols (incl. the 5GAA)
    - Information messages sent, specifically CAMs: they are time and safety critical, requiring low latencies
    - GDPR may become an issue when sending data from ADSs to NRAs (this could also be done via an intermediary service or back-end)
- Furthermore, ADS developers would like NRAs and road operators to send raw information to the ADSs, i.e. without pre-processing into a statistic or any prefiltering of the data.
    - Example reasons are how would you define traffic jam dissolution (i.e. when, how, and where is a traffic jam dissolving?), what is adverse weather (this is typically a combination of ice pockets, level of precipitation, friction indices, even oil spills), etc.?
- For automated vehicles, ODDs should be as defragmented (i.e. uninterrupted) as possible to ensure smooth operations.
    - This requires answering the questions: how is the ODD defined, and can you detect/confirm it?
    - In principle, vehicles have multiple sensors to deal with this
    - Landmarks and GNSS positioning require highly accurate digital maps
- For the interaction with the infrastructure, the ADS developers would like road operators to adopt and uphold the same standards as applied to the ADS vehicles.

- As data sharing from ADS developers to the infrastructure is a business case that involves, amongst others, road-quality data, there is a requirement to exclude liability, coverage, and funding of the data and sharing process
- Inter-brand connectivity should be pursued (in this respect, truck platooning is a good example)
- Traffic flow characteristics as attributes are not really picked up now by ADS developers, only for (optimal) speed advice, and GLOSA(-like) information
- Regarding the duration of ToCs:
  - There exist many studies regarding this topic. One such (Eriksson & Stanton 2017) reported that a human driver requires 1.9–25.7 s to safely take over the control of the vehicle after a take-over request depending on their mental workload. These studies have, in general, produced widely divergent estimates based on differences in experimental conditions and other assumptions. In essence, this as an area of continuing large uncertainty that is the subject of a lot of ongoing research effort.
  - OEMs are actively monitoring the driver in the vehicle in order to prevent long delays (i.e. getting the take-over times below 3 seconds (as stated during the workshop by some OEMs)

3.2.2 Stakeholders for CAD operations

In addition, according to the workshop on "Requirements to CAD system developers and operators and infrastructure evolution path" (TM4CAD, 2022), the following figure shows the relevant stakeholders for CAD operations.

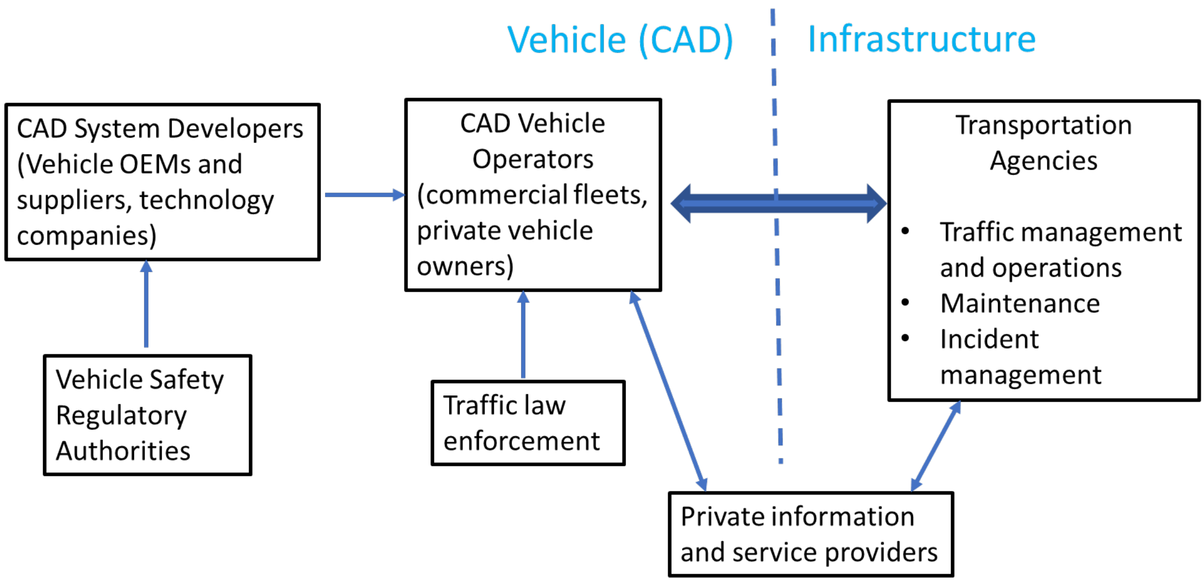

***Figure 2**: Stakeholder landscape for CAD operations.*

3.2.3 Minimal CAD system safety requirements

- Clear definition of ODD constraints, and limit automated driving to conditions within those constraints
- Respond to traffic controls and advisories (normal and incident management)
- Follow the applicable rules of the road in driving behaviours
- MRM to minimal risk condition in event of significant failure or violation of ODD limitations
- Notification of MRM (including why) to nearby vehicles and road authorities
- Fleet operations centres communicate with road authorities
- (External indication of automated operation is still under debate)

Other CAD system operational requirements are:

- Feedback to road operators on detected infrastructure condition problems
- Real-time incident reporting
- Variability in lateral positioning to distribute pavement wear (primarily for heavy vehicles)

Additional requirements could be:

- Curb access responses for drop-off – how to get around rules that are often violated by human drivers?
- Occupants leaving doors open, which may pose issues for robotaxis
- Follow routing advisories from TMC
- MRM clarification – not necessarily stopping right away – considering traffic safety – consider all causes for MRM trigger
- Notification to first responders as well as TMC

3.2.4 Infrastructure requirements

From the physical side we see the following requirements emerging:

- Minimal physical condition requirements (legibility of pavement markings or signs)
- “Safe harbour” locations where CAD systems can park vehicles that need to execute MRMs

From the operational side we have:

- Standardise traffic management message contents and encoding for consistent understanding
- Standardise road works and incident management site markings and notifications

From the digital side we have

- Communication of real-time ODD attribute status to provide CAD systems with promised level of distributed ODD attribute value awareness
- Rules of the road defined in “machine readable” form for use by CAD developers and operators (see also Annex)
- Certification needs and mechanisms

Lastly, but hitherto unspecified, environmental conditions may also play a role for the infrastructure.

3.2.5 Relevant questions and discussion topics

From our interaction with NRAs and ADS developers (e.g., the TM4CAD workshop in Lisbon, 2022), we obtained the following insights and relevant questions that serve as topics for further discussions between NRAs and ADS developers:

- We should not assume that all ADSs have the same capabilities
- There is an important difference between advisory and prescriptive traffic management
- It would be desirable that ODD defragmentation on a motorway is completely eliminated when going from L3 to L4
- We should keep track of where in the world relevant tests regarding ODD departures are being researched, e.g., exiting tunnels, etc.
- There are different interpretations of the ODD conditions and management by different brands or continents
- It is worthwhile to have an intermediary service provider that acts in between the vehicles/fleets and the TMC(s), mostly from a functional and organisational point of view
- It is more relevant to first think about functions before looking at organisational structures
- What constitutes an MRM?
    - Current automated lane keeping systems' regulation allows vehicle stopping on the hard shoulder at the side of the road
    - The way MRMs are executed should be discussed with ADS developers
    - MRM is the subject of current standardisation activity within ISO
- Statistics for high traffic volume roads on where MRMs occur; they are supposed to be rare events but knowing where they may increase in number may interesting for NRAs
- Information about MRMs should not just be communicated to road operators and/or fleet operations centres, but also to first responders

3.3 Publication of the requirements

In the following sections we elaborate further on the previous requirements, this time focusing on how to best convey them to the relevant stakeholders. One method is through holding an open stakeholder dialogue, in which requirements are to be published in specific (standardisation) bodies. Another method, which we deem more successful in the long term and has the ability to integrate all requirements, is by establishing a so-called codified highway code. In this section we focus on the former; detailed information on the latter can be found in Appendix A.

The most straightforward way of being inclusive and assuring that all relevant stakeholders are involved and in agreement, is by introducing all the requirements systematically into the relevant eco-systems. In addition to having one-on-one exchanges with all the various stakeholder groups (as already being done in the TM4CAD workshops, as well as those from previous and current related projects), there is another method to achieve this: by means of (standardisation) bodies. An effective way is then to document and publish the requirements through UNECE / ISO documents. This can also be seen as a prerequisite step in order to bring the guidelines for our proposed codified highway code to a regulating level.

The added benefit of TM4CAD is that it provides explicit links with distributed ODD attribute value awareness, which is directly relevant for road operators, and CAD developers (or AV fleet operators specifically) in particular. Through the detailed treatment given in the previous WP2-4 related documents, we are able to integrate isolated parts (e.g., ODD taxonomy, infrastructure, etc.) and have them one by one included in standardisation, opening the way to a broader adoption.

The results from all our open stakeholder dialogues (mainly through our workshops) are already incorporated in the various subsections of Chapter 3.

4 Critical remarks and recommendations

Given the requirements set out in the previous chapter, we wish to emphasise the need for an open dialogue between road authorities and operators (including TMCs) on the one hand and ADS developers (including Tier-1 providers) on the other hand.

A critical issue in this dialogue is a common understanding of expected behaviour of an automated vehicle or ADS. In order to have a successful integration, both road-side and on-board systems are required to work together. For road authorities and operators as well as TMCs, it is necessary to understand how a vehicle or ADS will react under certain conditions. Vice versa, for the ADS developers and fleet operators it is worthwhile to capture what the road infrastructure stakeholders expect from them and what they in turn expect from these stakeholders. This goes much further than just an exchange of data, as it puts the emphasis on driving behaviour as well, thereby having a close relationship with the rules of the road. These can, as explained in Appendix A, be codified in a manner that is unambiguous with regards to interpretation; while accomplishing this is certainly not straightforward, the hope is that this can nevertheless be realised.

Entering in such a dialogue would be beneficial for all parties as it further enables trust between them. This is necessary, as the requirements for DOVA are higher than those for 'regular' C-ITS systems, for which ADS developers are expected to only accept high-quality data. Conversely, road authorities/operators and TMCs would benefit from obtaining actual vehicle data in order to shape, test, and implement their policies.

A fruitful way for entering into this dialogue, is for the various standardisation committees to include people who will actually understand the implementation of traffic management scenarios on the one hand and ADS on the other hand. This understanding of the various aspects is a prerequisite, whereby all practitioners would also adopt a common terminology. Therefore, road authorities and operators should hire people that understand all of this.

A practical example that serves as a point in case, is the definition of an MRM. What is the MRM, and what is the ADS aiming to accomplish with it? How and when does an MRM occur? How is it leading to a safe condition? Going even further, a additional question to road authorities and operators is when is an MRC really a minimal risk one or not? The dialogue can also help settle debates on whether to stop the vehicle, or continue cruising at, e.g., 60 km/h (if the system can handle that at that moment for a certain time). In any case, road authorities and operators need information from the AV fleet operators and developers, or at least need to be involved in the conversation. At current, road authorities and operators have a lot of situations in mind about which they wonder "*How does an ADS react?*"

Road authorities and operators can then also put all their questions forward to the ADS developers. The work done in TM4CAD provides the road authorities and operators already with concrete, tangible, and relevant examples that allow them to start a discussion with the developers in order to know how to deal with the different situations (from a traffic management perspective) and how they (i.e. the vehicles) would deal with them.

5 Conclusions

The main objective of this deliverable was to provide a complete set of realistically implementable requirements, from traffic management systems and road operators, to CAD systems and automated vehicle manufacturers.

This entailed a collection of requirements, first from a technical point of view (for traffic management and CAD systems), and then highlighting the roles both the national road authorities (and traffic management centres) and vehicle technology developers (and Tier-1 providers) play in this respect. Most of the requirements were given at a higher level, based on the work done in WP2, WP3, and WP4, with extra inputs stemming from the MANTRA, EU EIP, and TransAID projects.

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- An infrastructure evolution path
- An overview of how the codified highway code works

➔ The workshop's aim was to pave the way to a more unified and cooperative roadmap.

Table 2: *Mapping of achievements and gaps to Research Questions and Expected Results*

Research question / result	Achievements and gaps
RQ1: Should NRAs set requirements on the desired behaviour of (partly) automated vehicles on where and how they should drive?	The answer is nuanced: the desired behaviour of (partly) automated vehicles should be defined as a product of the interactions between the NRAs and the developers of the vehicle technology to produce a balance between technological feasibility and serving transportation system needs. So, in practice this entails much more interaction between NRAs on the one hand and ADS developers on the other hand. Prime examples of such discussion items in which it makes sense for NRAs to be engaged as well are the definition of an MRM, what constitutes an MRC, what behaviour is expected from an automated vehicle or ADS (automated driving system), and what are the consequences of any road code requirements and decisions taken by an ADS?
ER3: Determination of the information needs and who is to provide this information in the bidirectional interaction between TMC and vehicle	There currently exists a large knowledge gap between both parties in this respect: NRAs do need to understand how an ADS will react under certain conditions, and ADS developers and operators need to understand what is expected by the NRAs in order to fine-tune their ADS' behaviours. In order to mitigate this, we recommend a mutual exchange of information in an open dialogue.
OR3: A vision on what requirements an NRA should set on the desired behaviour of (partly) automated vehicles, where and how they should drive	A vision for these requirements will typically be created from a perspective of vehicle safety. Safety for the vehicle, for the passenger, and for the environment (i.e. the other traffic participants). Based on a common understanding of the stakes involved, both NRAs and ADS developers can work together, and define what is realistically possible.

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Appendix A: Codified Rules of the Road

A.1 Concept

To enable the road operators to define *good behaviour* for CAD systems, the next step is the introduction of a novel codified rules of the road concept [1]. This is required along with a common set of ODD attributes, in similar spirit as to how a *regular* rules of the road[2] defines the expected behaviour from human drivers. This will enable manufacturers and road operators to communicate in a common, predefined language, and allow for changes in CAD traffic throughput due to ODD and infrastructure support changes. This good/expected behaviour of CAD systems will form part of a behaviour library, while operating conditions will be part of (instantiations of) the ODD. The benefit of this is that any CAD system, as well as road operators, can adopt and follow these codified 'rules of the road', with the goal of them being unambiguous, verifiable and explainable.

This method is already being discussed in the UK, based on road authorities' and manufacturers' needs and interests. Simultaneously, this approach will encompass expected behaviour in certain operating environments, therefore providing a close link with the ODDs. In the following, we give some insights into the process of turning the highway code into a more deterministic/mathematical format (Douglas, 2022).

Two of the relevant topics for CAD system driving safely are:

- The CAD system should comply with traffic rules.
- The CAD system should interact safely with other road users.

In addition, the CAD system should respond in line with traffic laws to markings and signals.

To this end, it becomes paramount to create verifiable requirements that can be used to create relevant scenarios. As an example, consider UK Highway Code Rule #195:

> "*As you approach a zebra crossing: look out for pedestrians waiting to cross and be ready to slow down or stop to let them cross; you MUST give way when a pedestrian has moved onto a crossing.*"

In the previous statement, we can make a distinction between behaviour and ODD-related information. However, a crucial question – and currently an assumption – for the CAD system here is: how long must (the vehicle) wait?

> **Current rules of road for human drivers**
>
> **= function(operating condition, behaviour competency, assumptions)**

By applying a rigorous codification process, the aim is to reach:

> **Codified rule of the road**
>
> **= function(operating condition, behaviour competency, driving characteristics)**

In the current setup, it is necessary to derive the right set of requirements. For the

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[1] UNECE FRAV 33rd Meeting: FRAV-33-39: (UK) An Approach to Defining Codified Rules of the Road

[2] A highway code is a set of information, advice, guides, and mandatory rules for road users in a specific country. Its objective is to promote road safety, and it applies to all road users including pedestrians, horse riders, and cyclists, as well as motorcyclists and drivers. It gives information on road signs, road markings, vehicle markings, and road safety. It can also give extended information on vehicle maintenance, licence requirements, documentation, penalties, and vehicle security. In an international context, a highway code may be following the treaty set out by the Vienna Convention on Road Traffic.

aforementioned rule, this becomes:

- The speed limit is the absolute maximum and does not mean it is safe to drive at that speed irrespective of conditions. Driving at speeds too fast for the road and traffic conditions is dangerous. You should always reduce your speed when:
    - the road layout or condition presents hazards, such as bends
    - sharing the road with pedestrians, cyclists, and horse riders, particularly children, and motorcyclists
    - weather conditions make it safer to do so
    - driving at night as it is more difficult to see other road users.

In a first step, we identify the different types of information as follows:

- speed limit is absolute maximum and does not mean safe speed
- reduce speed when:
    - road layout or condition hazards, bends
    - sharing the road pedestrians, cyclists, and horse riders, particularly children, and motorcyclists
    - weather conditions make it safer
    - driving at night

Aside from identifying non-informative text, we used the following conventions:

- Behaviour
- ODD
    - Scenery
    - Actor
    - Environment
- Rule/parameter qualifying
- Problematic word use

Finally, the next step is to convert this information into formal logic, as follows:

- isVehicle(x) → speed(x) < limit(speed)
- (near(x,a1) ∧ ¬isVehicle(a1))
- isVehicle(x) ∧ (isAtHazard(x) V
  (near(x,a1) ∧ isPedestrian(a1)) V
  (near(x,a2)) ∧ isCyclist(a2)) V
  (near(x,a3)) ∧ isHorseRider(a3)) V
  (near(x,a4)) ∧ isChildren(a4)) V
  (near(x,a5)) ∧ isMotorcyclist(a5)) V
  isUnsafeWeather(env) V
  isNight(tod))
  → action(reduceSpeed)

(here we used the logical symbols ∧ and V to denote AND and OR, respectively)

However, in the previous example we are still confronted with certain essential questions: what does "*near*" mean, what about "*hazard*", what is "*UnsafeWeather*"? Are we defining a vehicle as something that is anything with four or more wheels? What do we mean by "*slow speed*"? What is acceptable? And what do we mean by "*reduceSpeed*"? Answering these questions still requires quite active research, thereby specifically addressing the different ranges of parameter values that can be assigned to these, and then into the consequences of each of these choices. A possible approach to deal with this is to set up (sub)microscopic traffic simulations with dedicated controllers that regulate the car-following and lane-changing behaviour in line with the codified rules, and then assessing the impacts through a wide range of KPIs (including ones for safety, such as time-to-collision, etc.).

The ultimate goal here is then to apply this process and to codify all the Vienna Convention Rules of the Road, as well as the national specifics. These rules by themselves also contain ample statements are left open to interpretation and thus need to be cleared before codification. For example:

- Article 7 (General rules):
    - (3) Drivers shall show extra care in relation to the most vulnerable road users, such as pedestrians and cyclists and in particular children, elderly persons, and the disabled.
    - (4) Drivers shall take care that their vehicles do not inconvenience other road users or the occupants of properties bordering on the road, for example, by causing noise or raising dust or smoke where they can avoid doing so.
- Article 11 (Overtaking):
    - (1.4) When overtaking, a driver shall give the road user or road users overtaken a sufficiently wide berth.

For the latter, the codification process would entail first:

- When overtaking, a driver shall give the road user or road users overtaken a sufficiently wide berth.

Which is then turned into the following formal logic:

- isVehicle(x) ∧ onRoad(x,r) ∧
  roadUser(y,r) ∧
  isOvertaking(x,y) ∧
  lateralDistance(x,y,z)
  → sufficientlyWideBerth(z)

A similar article yields the following:

- A vehicle shall not overtake another vehicle which is approaching a pedestrian crossing marked on the carriageway or signposted as such, or which is stopped immediately before the crossing, otherwise than at a speed low enough to enable it to stop immediately if a pedestrian is on the crossing.

Overall, the previous serves to show that it is useful to use ODD-based rules of the road to attain a wider safety assurance. Hence:

- Each rule of the road (anywhere) will always be a function of ODD and behaviour competencies
- Each scenario (irrespective of the system under test), will always have ODD attribute information and behaviour information.

All this information can be mapped using labels/tags.

A.2 Implementation

It makes sense that the responsibility for the initial approach to the implementation, that is, construction, of a codified rules of the road, lies with the NRAs, or broader (local) governments. However, the identification and explanation of the driving characteristics need to be done by the CAD system developer to the authorities. In order to facilitate this in a smooth way, the CAD developers should be involved very early on, given that their vehicles will have to work and deal with the code in a wide variety of real-life conditions. In addition, it seems that the CAD developers have lot more to potentially gain, so one could argue that the burden (and cost, especially) should be shared by them as well.

At current, this approach was presented by the UK at the UNECE FRAV informal working group and is being discussed at the forum. Further insights need to be developed, as there is the risk that a codified rules of the road will not be able to deal with all possible situations on the road. If we assume that the highway code for human drivers encompasses all known rules for operating a vehicle on the road under all conditions, then there is less of a problem. However, that is based on an assumption, while it is more rational to state that these limited scenarios do not encompass the entire span of possible interactions between vehicles, infrastructure, and any other traffic participant. Only complying with these scenarios would then incur unforeseen risks, where it would be better that a broad testing is foreseen by having NRAs cooperate closely with the OEMs.