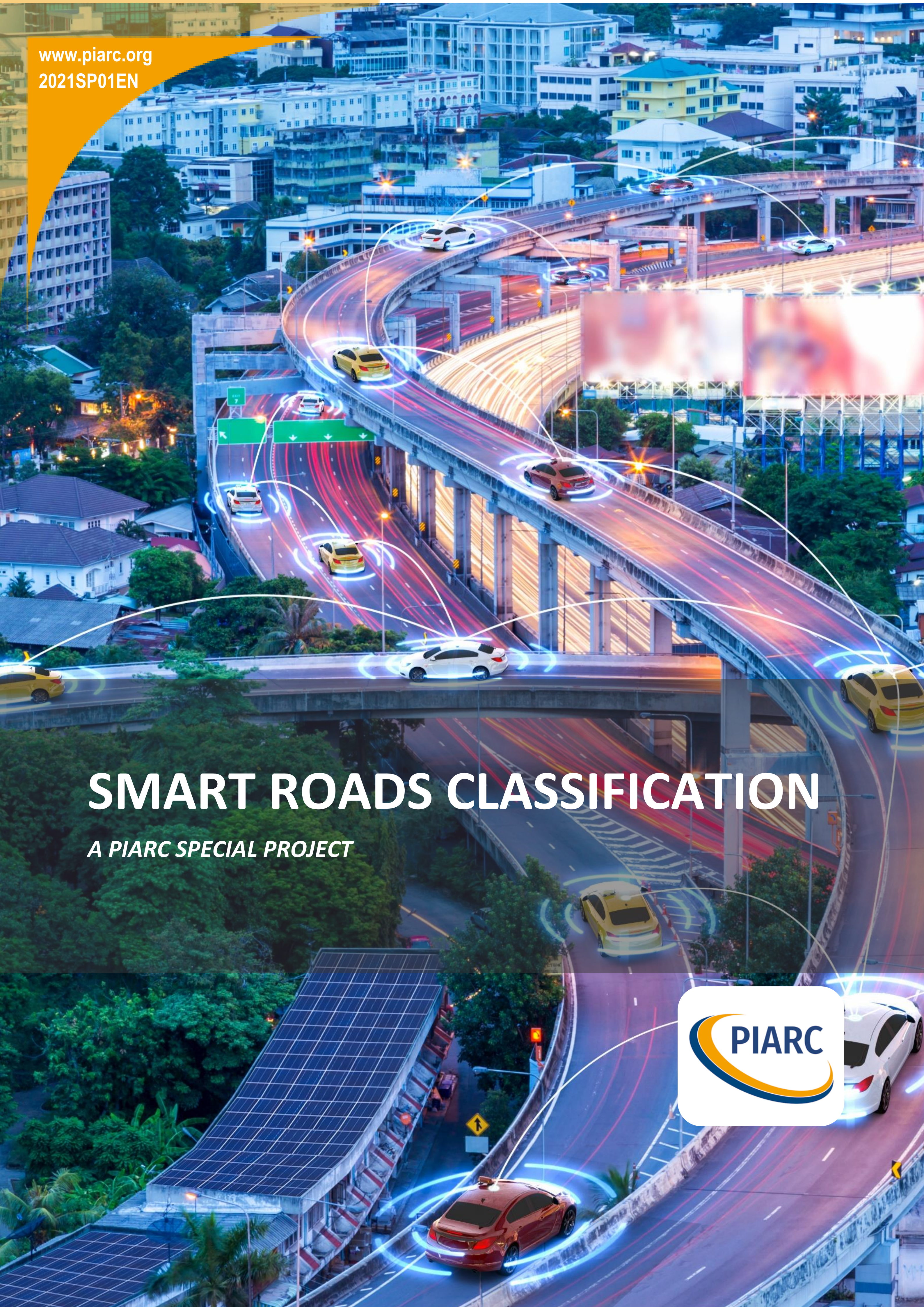

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SMART ROADS CLASSIFICATION

A PIARC SPECIAL PROJECT

PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

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This report was approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

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EXECUTIVE SUMMARY

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SMART ROADS CLASSIFICATION

Traditionally, road network classification systems have focused on two fundamentally opposite dimensions: mobility and accessibility. These classification systems have been adapted to the variable circumstances of countries or regions. However, with Connected and Automated Vehicles (CAVs) coming into play, the situation has become quite more challenging than before.

Current CAVs consist of diverse Advance Driver Assistance Systems (ADAS) that assist humans in the driving task. The automotive industry is carrying out a great research effort, so the most advanced systems can even control the vehicle operation. However, there is a plethora of different systems, varying in how this assistance is performed. As a result, not all CAVs perform in the same way and, what is more, this performance is evolving over time.

In order to clarify the capabilities of these new vehicles, the Society of Automotive Engineers (SAE) developed a classification system that grouped these capabilities in six levels. SAE level 0 applies to human-driven vehicles. SAE level 1 refers to driving automation systems that can either control the longitudinal or the lateral position of the vehicle. SAE level 2 refers to the systems that can control both –longitudinal and lateral position– at the same time. In these cases, the system is considered to just assist –not replace– the human. Moreover, these systems are not infallible and may suddenly disconnect –i.e., disengage– releasing the control to the driver, who must be attentive to the road.

SAE level 3 goes a step further, being able to control more situations and preventing disengagements. These vehicles are supposed to foresee disengaging situations and request the driver intervention in advance. SAE level 4 vehicles are expected to be fully autonomous within a certain region that meets certain characteristics –called Operational Design Domain, ODD– not needing the intervention of a human in these zones. Finally, SAE level 5 vehicles are expected –in a distant future– to be fully autonomous regardless the zone they are driving through.

Nowadays, the Penetration Market Rate of SAE level 2 vehicles is on the increase, and the first SAE level 3 vehicles are showing up. There are three important challenges to the deployment of CAVs:

1. Safety concerns due to disengagements. A driver would probably disable the driving automation system at medium-to-sharp roads, with many disengagements that prevent a smooth automation. On the other hand, freeways may present a very good, automated experience, but a sudden disengagement may have severe consequences on a distracted driver.
2. Given the variety of driving automation systems, a certain road may trigger a disengagement in some vehicles and not in others. As a result, roads cannot be directly classified according to a sort of 'automation-readiness' parameter. Instead, many factors intervene on disengagements and Take Over Requests (TOR), and have to be evaluated for any single driving automation system.
3. There is a lack of information for drivers about automation. Drivers are sometimes misinformed about the capabilities of their own vehicles. More information should be provided to all citizens about what is a driving automation system and the importance of being attentive to the road with up to SAE level 3 vehicles.

These barriers would not prevent automation but slow down its deployment. Customers may be reluctant to acquire and use these technologies if they do not see relevant advantages, even more if there are safety concerns due to disengagements.

It seems clear that to promote a quick and reliable expansion of Automated Vehicles, customers need to trust in their capabilities. In other words, the driver should not subjectively decide whether to connect the driving automation system or not. This decision should be objective, e.g., based on information provided by combining the characteristics of the infrastructure with the capabilities of the driving assistance system.

In addition to the development of Automated Vehicles, there is also a boost in making use of connectivity and information-sharing to further enhance traffic operation and safety. Connecting all elements (vehicles, road users, infrastructure, traffic, weather data, etc.) will lead to better knowledge of the traffic conditions and events throughout the road network, which will help improve traffic flow, reduce road crashes, and minimize vehicle emissions. A digital infrastructure that provides this information is being outlined, as well as how it would be provided to users.

Connectivity could improve automation –where available– and traffic performance, especially high-volume road facilities. This is why automated and connected driving goes hand in hand with different political goals that the European Commission, the United States, the United Kingdom, and China have been pursuing for years, most of them related with safety and the reduction of fatal crashes.

Considering the variety of road facilities and connectivity capabilities to come, recent few research projects have pointed out the necessity to explore a Smart Roads Classification (SRC) that helps CAVs and users know what to expect from the different road facilities. This information should range from road segments that do not support automation, to road segments that will even be able to take control of thousands of vehicles at a time to optimize safety and performance in a cooperative way.

An SRC should therefore comply with certain objectives, highlighting the following ones:

- Safe, operational, and sustainable. An SRC should increase the road safety levels, either by presenting an adequate geometry, signage, and pavement condition that prevents most disengagements, or sharing detailed information with connected vehicles. In addition, it should improve traffic performance and help reducing vehicle emissions.
- Universal framework. An SRC should be fully compatible, but adaptable, everywhere and could be used by any road facility, vehicle, and user. This is a very strong challenge due to the worldwide diversity of roads, regulations, and users.
- Flexible. Given the fast technology evolution of CAVs and the vast road network, an SRC should be resilient to technological changes that affect how users interact with the infrastructure.
- Robust and dynamic. To provide coherent information to users, adaptive to changing situations in real-time.
- Simple and credible. An SRC should be an easy-to-use tool for all stakeholders (Road Administrations and Operators, automotive industry, road users, etc.), so they can easily interpret what to do. This does not mean simplicity in the data to be shared with vehicles. As an example: a road with detailed digital information to host automation may share microscopic traffic data with vehicles but should show a unique sign to drivers indicating

that this road facility presents this capability. It is very important an SRC to be credible, indicating the capabilities that the road has, not more (possible safety concerns) or few (lower credibility of users on the SRC).

- Fair share of responsibilities between all involved stakeholders. This is of special importance for Road Administrations and Operators, who should set an adequate Smart Road Level (SRL) and look for its maintenance –or changing it when needed–. This SRL is merely informative, being road users responsible for performing accordingly to it and the automation capabilities of their vehicles. Moreover, any minimal mismatch between the shown SRL and the actual SRL by RAs or ROs should only result in performance loss, not impacting safety.

Opportunities and Challenges

Given the necessity of an SRC to be a universal framework, a questionnaire was launched to retrieve opinions and thoughts from different stakeholders worldwide. One of the key aspects was to identify the opportunities and challenges that an SRC should present. It is important to highlight that these opportunities and challenges are exclusively related to an SRC and not to CAVs, which have different ones.

The **most important benefits and opportunities of an SRC** are:

- Efficient planning of investments on physical and digital infrastructure. Smart Road Levels (SRLs) should be based on physical and digital information of roads. The requirements for each SRL should be clear. RAs and ROs could compare their road networks to these criteria to find where their investments would have the highest impacts on automation. Other data such as traffic volumes, crash rates, etc. should also be considered.
- Establishment of no-regret investments (especially for high-end CAVs). OEMs are continuously updating the driving automation systems with new features, improving the scenarios where CAVs can perform. On the other hand, several researchers have outlined that the road infrastructure could also be adapted to existing CAVs' capabilities, which would result in a faster deployment of CAVs. Investments on road infrastructure are very expensive, so it is very important that they are planned adequately. An SRC could prevent unnecessary investments –e.g., cutting-edge connectivity features in a road facility that cannot support automation due to its geometry–.
- As indicated above, driving automation systems are continuously being improved by OEMs. However, these efforts are being carried out in many different directions. The result is a lack of uniformity on where the different CAVs can perform. An SRC would present clear thresholds for the different Smart Road Levels, which could be used by OEMs to point their efforts. This could result in a certain convergence of CAV capabilities.
- Clear and simple indication for users. As indicated above, an SRC should present clear messages to users, explaining what to expect from the road facility regarding automation and connectivity –e.g., recommendation to enable the driving automation system, availability of connectivity, etc.–.

The **most remarkable challenges and barriers of an SRC** are the following ones:

- Lack of coordination and cooperation between stakeholders. Many stakeholders are involved in the process (Road Administrations and Operators, Users, Original Equipment Manufacturers, etc.). All these actors should come to different agreements as CAVs –

especially the highest SAE levels– are introduced in the market. An SRC would add more aspects to agree on, such as the number and properties of the SRLs, implementation procedures, how they relate to vehicles and other users, how the cooperative driving and perception operate, etc.

- There are still too many uncertainties in several aspects, such as how the automation technology will evolve in the very near future (i.e., the immediate SAE level 3 vehicles to come). Many efforts are being carried out to establish a digital infrastructure, but how it will be provided to vehicles, what information should contain, and how it should be organized, are still under discussion.
- Heterogeneity across countries. A uniform SRC across countries is a hard goal to achieve, but it gets even more difficult given the variety of situations of the different countries. The new road guidelines should meet the requirements established by the SRC but should also be based on the national/regional previous regulations. Adaptation to the new requirements should be performed gradually in time.
- Costs. Finally, an extensive digital infrastructure is expected to be deployed, supporting the digital information for road users. Regardless how it is achieved, it remains clear that these would imply significant costs that are still to be determined. This also applies to the maintenance and update of the network. There are different scenarios about how these costs could be addressed.

Feasibility

After determining that an SRC would be useful to deploy CAVs in a faster way and better target the investments, it is necessary to outline its possible levels and constraints. These are presented after introducing the involved stakeholders and the possible future scenarios.

Involved Stakeholders

Many different stakeholders intervene in the management of a road network with mixed traffic involving CAVs. The following ones can be highlighted:

- Road Administrations (RAs). These own the road infrastructure and are usually in charge of the planning and investment of new facilities.
- Road Operators (ROs). They are in charge of the traffic operation and safety management, ensuring adequate conditions for users. There is a high diversity about how responsibilities are shared among RAs and ROs.
- Original Equipment Manufacturers (OEMs). Automakers and their suppliers (TIER1s) are working hard expanding the capabilities of CAVs. These capabilities are evolving fast and would be gradually expanding where automated vehicles can operate.
- Mobile Network Operators (MNOs). These stakeholders are the providers of the wireless connectivity that could serve as a basis for C-V2X communications.
- Users. These are the most important agents, since will interact along the road facilities. Tailored information regarding infrastructure and vehicles should be provided for them to ensure a good performance and a fast adoption of CAVs.
- Information Management Providers (IMPs). Once the Digital Infrastructure is available and connected vehicles become a reality, a lot of information related to performance, road maintenance, etc. will be shared. There is a necessity to collect, process, and share this information with the adequate stakeholders. Information Management Providers cover the

stakeholders that will intervene in this process. Other stakeholders such as services providers, trip planners, MaaS providers are part of this group.

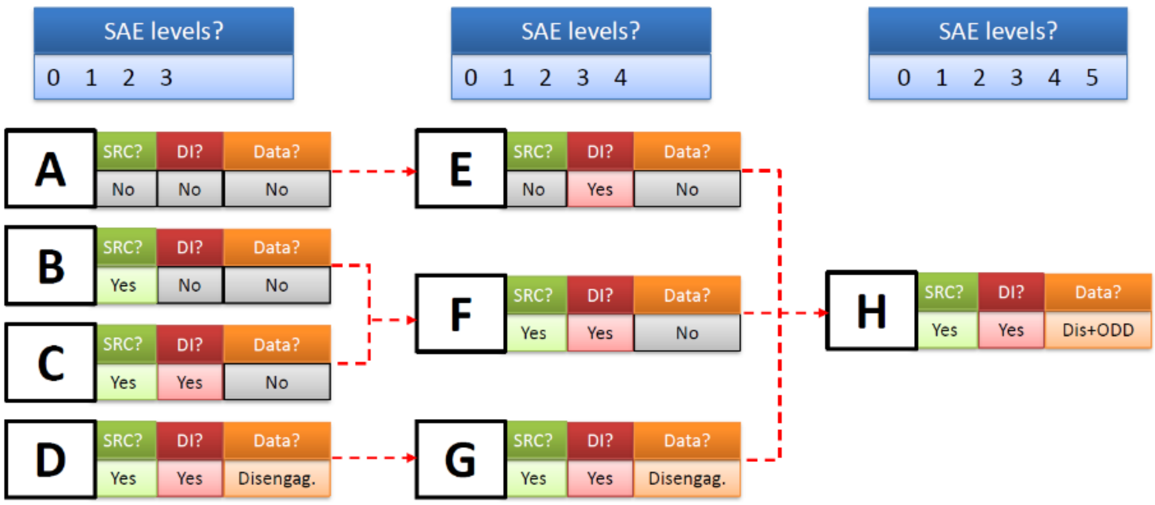
These definitions are general and may vary across countries and in time.

Scenarios

The high uncertainty indicated above prevents us from giving clear indications about how an SRC should be. In addition, an SRC should vary in time, creating new levels when CAVs with more advanced features show up in the market. Most of this uncertainty can be classified depending on four different factors:

- SRC application (yes/no). This factor indicates, for each scenario, whether a Smart Roads Classification system exists and can be applied to all or part of the road network. Scenarios without SRC are considered as base conditions, which could be used to highlight the differences with scenarios including an SRC.
- SAE levels on the market (levels 0 to 5). This factor indicates which SAE levels operate on the road network.
- Digital Infrastructure (yes/no). This factor refers to whether a Digital Infrastructure exists and is available in all or part of the road network. With the existing trend, its existence is considered very likely in a medium-term, and plausible in a short-term. This factor does not refer to the data structure or how data are shared with vehicles and users.
- Existence of data about disengagements and Operational Design Domains (ODDs) (no / only disengagements / disengagements and ODD). Some researchers and institutions have suggested OEMs to share the disengagement data of their vehicles publicly to better know the triggering factors behind them. This would be helpful for RAs and ROs to know which facilities should receive attention regarding automation. A further step would be sharing detailed data about the environments that can be driven in an automated way (Operational Design Domains, ODDs).

These variable factors can be organized into eight scenarios, as shown in Figure I and described below.



- Scenario A represents a very near future for the existing situation. In it, there are up to SAE level 3 vehicles, an SRC does not exist, a digital infrastructure is not available, and disengagement data is not publicly available. SAE level 2 vehicles present disengagements and SAE level 3 vehicles present Take Over Requests with variable timing. Drivers would not have clear insight about where they should activate their driving automation systems. However, they could figure it out as they get more familiar with their vehicles. Some private systems could also provide this information. Information campaigns should be promoted to force driver attention even where SAE level 3 vehicles present very few disengagements –a distraction could be fatal–.

- Scenario B adds an SRC to scenario A. Without a digital infrastructure that supports vehicle connectivity, this SRC should focus on recommending drivers where to enable or disable their driving automation systems based on the physical infrastructure features. Given the variety of the CAV capabilities, these indications should be established in a conservative way, i.e., clearly indicating the road segments that could be run automatedly by very few vehicles (e.g., red level), and the road segments that could be run automatedly by far most vehicles (e.g., orange level). Authorities should perform research campaigns to determine CAV limitations and therefore establish adequate thresholds. Intermediate thresholds could be also set if the variety of CAV performance is too high.
- Scenario C adds a digital infrastructure to scenario B. This does not mean that all road segments must present connectivity support, but that some road segments may have it. These road segments could therefore share valuable information with vehicles, such as road geometry, traffic performance, roadside status, etc. This information could be interpreted by CAVs to foresee disengagements and even avoid some of them. This would be very important to SAE level 3 vehicles. An SRC should therefore present a specific level for road segments with this feature and that physically can support automation (e.g., yellow level). This situation should be indicated to users by means of a physical sign or Variable Message Signs. Red level road segments with connectivity capabilities should still remain in red, given that the connectivity features would presumably not be enough to allow automation.
- Scenario D is very similar to scenario C, but having public information about disengagements, provided by OEMs. This scenario is particularly interesting for Road Authorities, since no research campaigns would be needed to establish the thresholds for the different Smart Road Levels. Road Authorities and especially Road Operators would benefit from this real-time disengagement data, by rapidly detecting zones with sudden increase of disengagements.
- Scenario E is the natural evolution of scenario A. In this case, SAE level 4 vehicles exist in the market, a digital infrastructure is also available, and an SRC does not exist. The digital information provided to vehicles would help them foresee and avoid some disengagements. However, it remains unclear where drivers can expect this information to be available or not. Non-connected SAE level 2 and 3 vehicles would still present the same limitations than for scenario A. SAE level 4 vehicles might not fully benefit from their capabilities, since it remains unclear to vehicles where they are exiting the ODD-compatible zones. Private services could supply this information, though.
- Scenario F is the natural evolution of scenarios B and C. Compared to scenario E, it adds the existence of an SRC. Having an SRC is particularly important with SAE level 4 vehicles, since they cannot present disengagements within their ODD-compatible zones. Therefore, road segments with very good physical properties –which meet nearly all SAE level 4 ODDs– and present good connectivity features could be tagged with a new Smart Road Level: the green level. This level indicates that a driver of a SAE level 4 vehicle can fully release control to

the vehicle, since it would not request manual control. Drivers of lower SAE levels would experience very few disengagements. The previous Smart Road Levels would coexist in other zones with worse physical properties. In order to improve traffic performance when SAE level 4 vehicles become general, a new Smart Road Level (blue level) is suggested. This level presents exceptional connectivity capabilities that support cooperative driving (i.e., the infrastructure can fully or partially control the vehicles, improving traffic performance, reducing vehicle emissions, etc.). This category should only be used at critical facilities to boost capacity, since only SAE level 4+ CAVs would be allowed (the vehicles that can support cooperative driving and meet the ODD).

- Scenario G. This scenario is similar to scenario F, adding real-time disengagement data from vehicles. Like scenario D, this information does not require new levels from the SRC but adds the possibility of a real-time management by RAs and ROs, reducing the need of public research on CAV limitations.
- Scenario H. This is a long-term scenario, in which SAE level 5 vehicles would be available too. SAE level 4 vehicles would be still a majority, and lower levels might exist but would not be common. Obviously, digital information is available in near all the road network. An SRC is considered necessary to determine where non-CAV vehicles are not allowed (i.e., the blue level). Despite the green level, lower levels may not be necessary in rural environments, given the large ODDs expected.

All scenarios requiring the deployment of a digital infrastructure (C to H) involve significant investments and maintenance costs. There are many different alternatives to make the new smart road system viable. RAs may make the entire investment in the deployment of the digital infrastructure, modify existing concession contracts, or even make new concessions with ROs and/or MNOs. There could be several sources of revenue, depending on the stakeholder:

- Providing physical and digital infrastructure and traffic data.
- A subscription fee for the connectivity service and a temporary service fee.
- An additional road tax for the purchase of CAVs or Connected Vehicles (CVs).
- Increased toll rate or pay-per-use fee.
- Increasing the number of 5G clients with a higher subscription.
- Receiving personalized information from a provider.
- For users providing data from their vehicles on road conditions and disengagements.

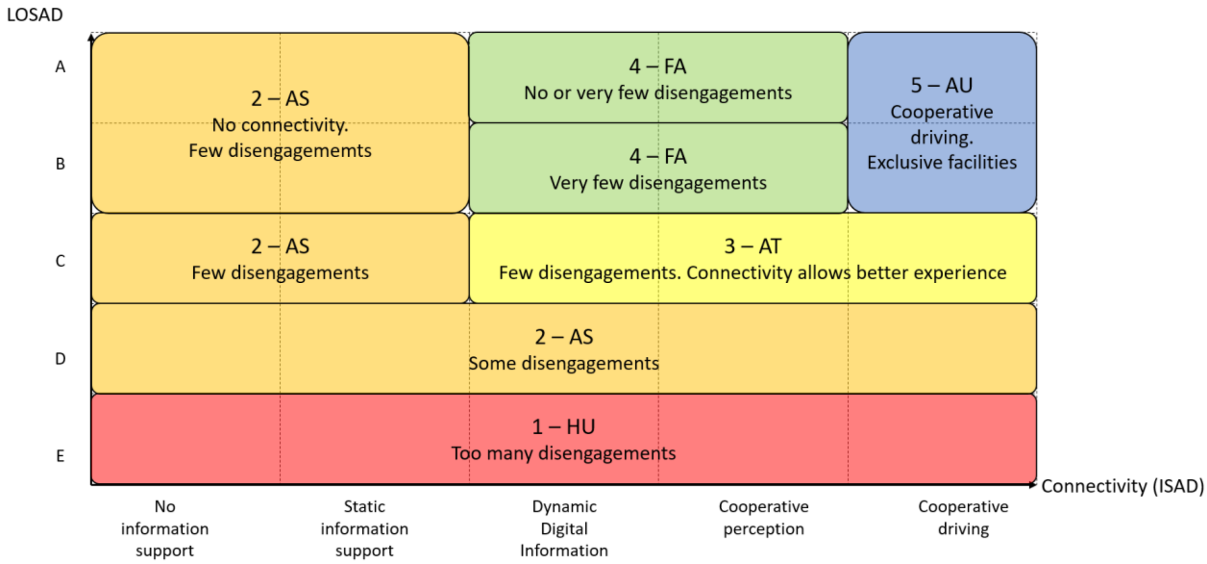
SRC Proposal

Considering the previous scenarios, a five-level SRC is suggested. Its Smart Road Levels correspond to the color-based scale used in the scenario description, summarized as follows:

- Humanway (HU) road segments. These road segments do not support automation. Drivers are discouraged from enabling their systems.
- Assisted way (AS) road segments. These road segments present partial support for automation, with remarkably less disengagements than on HU road segments.
- Automated way (AT) road segments. These road segments present similar physical characteristics than AS road segments, but also present connectivity capabilities that could help connected vehicles prevent and avoid disengagements.
- Full Automated way (FA) road segments. These road segments present full support for SAE level 4 vehicles, and good connectivity capabilities.

- Autonomous way (AU) road segments. These road segments present full support for SAE level 4 vehicles and exceptional connectivity capabilities. They can only be used by SAE level 4 and 5 vehicles.

As indicated before, road authorities should establish which properties and thresholds should be considered to define the levels. A first approach to which aspects might be considered has been addressed in the Special Project. Two indicators have been proposed: the Level of Service for Automated Driving (LOSAD) and the Infrastructure Support for Automated Driving (ISAD). The first one represents the physical readiness of the road segment to support automation, while the second one focuses on the connectivity support. Thus, the SRL could be determined by combining them as shown in Figure II.



Recommendations for an SRC Implementation

This Special Project presents an exploratory study about the feasibility of a Smart Roads Classification system. Identifying which steps should be done first becomes crucial. One of the activities of the Special Project was exploring the feedback about follow-up proposals from several stakeholders. The most important contributions are outlined here.

Road Administrations and Road Operators

RAs and ROs should define a clear physical sign to identify HU and AS road segments (in an advisory, non-mandatory way). HU road segments should be a priority, indicating drivers when the automated driving is clearly discouraged. A second step could be identifying AS road segments, i.e., which road segments present physical features that allow automation on most existing SAE level 2 vehicles.

Once the Digital Infrastructure is available, and RAs and ROs incorporate it to some road segments, AT road segments could be identified. It is important that connectivity is deployed to road segments that support automation.

These measures should go hand in hand with information and education campaigns to drivers and other users. They should be aware of what an automated vehicle can do. Keeping the driver attentive to the road is essential before SAE level 4 vehicles are a reality.

Regular updates to the SRC thresholds could be applied, adapting to the evolution of CAV capabilities. Pilot tests are considered a key factor. These can be used to check the connectivity and automation capabilities of CAVs under real-world conditions.

Automotive Industry

A critical key issue to be addressed is how to involve the automotive industry in the development and application of the SRC. Their collaboration has been remarkable scarce in the Special Project, probably due to the lack of information needed to develop their vehicles. This situation may change in the future, as traffic performance data is needed by higher Smart Road Levels.

Some proposals for RAs and ROs to look for OEM collaboration are:

- Collaborate with OEM platforms and not with individual OEMs.
- Discuss on SRC development and application in automotive meetings, forums, and standard committees. RAs and ROs should participate in the UNECE World Forum for Harmonization of Vehicle Regulations (WP.29) discussion on technical requirements for automated vehicles.
- OEMs are encouraged to provide information on disengagements. This would facilitate real-time management and data support to establish clear thresholds for the SRLs.
- OEMs should provide information about their ODDs, LOSAD- and ISAD-related factors.
- The Automotive Industry should be engaged in the development of the SRC, establishing a strong connection with RAs, ROs, and MNOs.

Mobile Network Operators (MNOs)

These stakeholders should be involved in the application of a SRC through pilot tests focused on main highways.

Users

Being users the center of the SRC proposal, the following recommendations are provided:

- Users must be informed about the capabilities of their Automated Vehicles. Different measures should be used, including education, training, etc.
- Users should receive clear and simple information about the SRLs.
- Users should be able to know the smart properties of the roads involved in an itinerary. This includes interaction among RAs, ROs, and IMPs.

Information Management Providers

These stakeholders will collect, process, and share information with all other stakeholders. Communication with RAs and ROs should be very direct, given the massive data exchange for a road network.

PIARC

It is not suggested that PIARC undertakes an additional Special Project on this topic until smart roads become more mature. Other possible actions could be done, such as webinars, conferences, dissemination of best practices and findings from SRC pilot studies, etc.

LMICs

Considering that Low-Medium Income Countries present many constraints, their global priority should be set to shift from Humanways (HU) to Assistedways (AS) as many roads as possible, starting with main highways and corridors. In addition, if the situation of the country allows it to plan and construct new road facilities, these should be designed to achieve the highest Smart Road Levels (SRLs). For that purpose, their actions should be directed towards implementing and expanding their 5G coverage, at least along their main corridors.

Considering the low adaptation to standard condition of many features of the road infrastructure, the upgrading of some highways to Assistedway (AS) will encourage safer roads for both human-driven vehicles and automated vehicles. Therefore, the benefits will be higher than in other countries with this first step. For that purpose, some road infrastructure improvements should be developed (e.g., pavements must be free of distresses and major irregularities, road markings must be wide enough, continuous, and in good enough condition to be visible, vertical signs must be adequate, etc.).

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

3GPP – 3rd Generation Partnership Project

5G NR V2X – Direct communication specified by 3GPP R16 based on a new radio (NR) interface

5GAA – 5G Automotive Association

AADT – Annual Average Daily Traffic

AASHTO – American Association of State Highway and Transportation Officials

ACC – Adaptive Cruise Control

ADAS – Advanced Driver Assistance Systems

ADS – Automated Driving System

AI – Artificial Intelligence

AS – Assistedway Smart Level

ASAM – Association for Standardization of Automation and Measuring Systems

AT – Automatedway Smart Level

ATC – Spanish National Committee of PIARC

AU – Autonomousway Smart Level

AV – Autonomated Vehicle

AVRI – Autonomous Vehicles Readiness Index

BSI – British Standards Institution

C-ITS – Cooperative Intelligent Transport System

C-V2X – Cellular V2X (Vehicle-to-Everything)

CAM – Connected and Automated Mobility

CAV – Connected and Automated Vehicle

CDOT – Colorado Department of Transportation

CMOS – Complementary metal-oxide-semiconductor

CRCS – Connected Roadway Classification System

DDT – Dynamic Driving Task

DGT – Spanish General Directorate of Traffic

DL – Dedicated Lane

DOT – Department of Transportation

DSRC – Dedicated Short-Range Communication

EAPA – European Asphalt Pavement Association

ERA – Emergency Refuge Area

ERS – Electric Road System

ETSI – European Telecommunication Standards Institute

EU – European Union

EU EIP – European ITS Platform

EV – Electric Vehicle

FA – Full Automatedway Smart Level

FCS – Functional Classification System

GCI – Global Connectivity Index

GDP – Gross Domestic Product

GNSS – Global Navigation Satellite System

GTSDB – German Traffic Sign Detection Benchmark

HD – High Definition

HERG – Highway Engineering Research Group

HMI – Human Machine Interface

HU – Humanway Smart Level

ICT – Information and Communications Technology

IEEE – Institute of Electrical and Electronics Engineers

IMP – Information Management Provider

IMU – Inertial Measurement Unit

INFRAMIX – Road INFRAstructure ready for MIXed vehicle traffic flows

IOO – Infrastructure Owner/Operator

IoT – Internet of Things

ISAD – Infrastructure Support Levels for Automated Driving

iTEAM – Institute of Telecommunications and Multimedia Applications

ITRAT – Institute of Transportation and Territory

ITS – Intelligent Transport System

ITS-G5 – European implementation of WLANp based on IEEE 802.11p or extended IEEE 802.11bd

KPI – Key Performance Indicator

LCA – Lane Centering Assist

LDW – Lane Departure Warning

LFM – LED Flicker Mitigation

LiDAR – Light Detection and Ranging

LKA – Lane Keeping Assist

LMIC – Low- and Middle-Income Country

LMV – Light Mobility Vehicle

LOS – Level of Service

LOSAD – Level of Service of Automated Driving

LTE – Long Term Evolution

LTE-V2X – Direct peer to peer short range communication in 5.9 GHz

MMS – Mobile Mapping System

MNO – Mobile Network Operator

MOR – Meteorological Optical Range

MRC – Minimal Risk Condition

MRM – Minimal Risk Maneuver

MUTCD – Manual on Uniform Traffic Control Devices

NCHRP – National Cooperative Highway Research Program

NHP – Neutral Host Provider

NIC – Next-generation Interchange Control

NR – New Radio

NR-V2X – Vehicle- to-Everything (V2X) standard based on the 5G New Radio (NR) air interface

ODC – Operational Design Condition

ODD – Operational Design Domain

OEM – Original Equipment Manufacturer

ORS – Operational Road Section

PIARC – World Road Association

PMR – Penetration Market Rate

POT – Project Oversight Team

QoS – Quality of Service

RA –Road Administration

RO – Road Operator

ROD – Restricted Operational Domain

ROI – Region Of Interest

RSU – Roadside Unit

RTK – Real-Time Kinetics

SAE – Society of Automotive Engineers

SRC – Smart Roads Classification

SRL – Smart Road Level

TIER1 – Company that supplies systems directly to OEM

TLR – Traffic Light Recognition

TOC – Traffic Operation Center

TSR – Traffic Sign Recognition

UPV – Universitat Politècnica de València

V2I – Vehicle-to-Infrastructure

V2N – Vehicle-to-Network

V2P – Vehicle-to-Pedestrian

V2V – Vehicle-to-Vehicle

V2X – Vehicle-to-Everything

VMS – Variable Message Sign

WAVE – Wireless Access in Vehicular Environments

WLAN – Wireless Local Area Network

1. INTRODUCTION

1.1. BACKGROUND

Traditionally, road network classification systems have focused on two fundamental opposite dimensions: mobility and accessibility. Since its inception, this classification system has evolved with the intention of adapting to the new circumstances of society. This is the case of the proposed classification system of the Interurban Roads Technical Committee of the Spanish National Committee of PIARC (ATC) [1], which included as main factors the economic-administrative functionality, the administrative ownership, the technical functionality, the morphology of the road, and the environment; and the Expanded Functional Classification System [2] proposed recently in the United States to integrate the different types of users. Specifically, this classification system combines two of the criteria defined by the ATC Committee –environment and technical functionality– with the type of user.

However, none of these classifications considers the incipient appearance of Connected and Automated Vehicles (CAVs) on our roads. A new Smart Roads Classification (SRC) system for the road network is therefore required. In this context, two research projects have recently finished integrating the particularities of CAVs in road classification: Connected Roadway Classification System [3] and INFRAMIX [4]. The first one established a road classification based on three approaches: talking (vehicle-infrastructure communication), seeing (infrastructure readability), and simplifying (design and operations for automated vehicles); whereas the second one proposed a road classification focusing mainly on vehicle-infrastructure connectivity.

Existing Automated Vehicles consist of diverse Advanced Driver Assistance Systems (ADAS) that allow an automated driving experience under specific circumstances. Their role in the driving task has become so important that the Society of Automotive Engineers (SAE) proposed a 6-level classification of automation based on how human and vehicle share the driving task [5] (Figure 1).

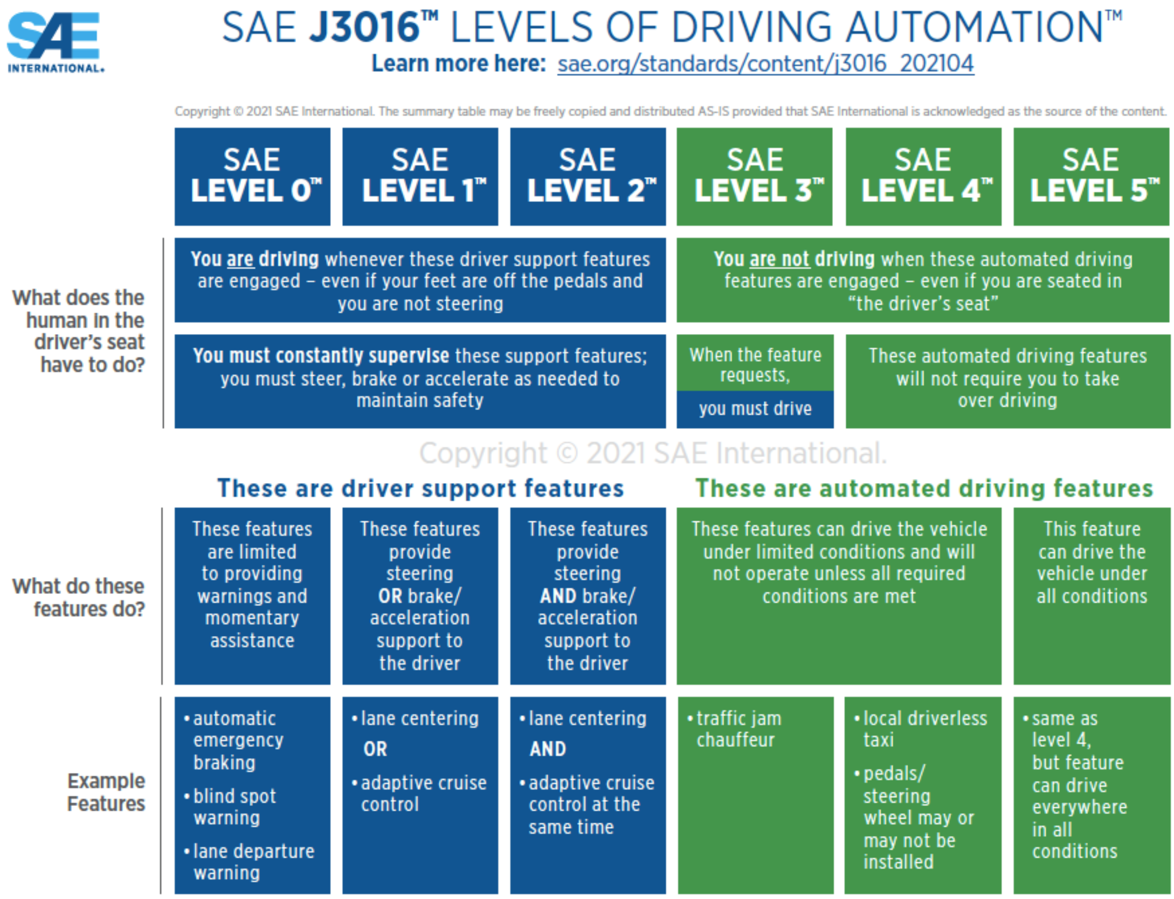


Figure 1. SAE J3016 Levels of Driving Automation. Source: SAE, 2021 [5].

The extremes –SAE level 0 and SAE level 5– are easy to be understood, with SAE level 0 meaning that there is nothing in the car that will ever take control of any of the car's movement functions, and SAE level 5 meaning full autonomy (Figure 1). However, the intermediate levels are a bit more blurred. To this regard, the SAE and ISO have recently defined the first three levels (SAE level 0, 1, and 2) as "Driver Support Systems", while SAE level 3, 4 and 5 should be used for actual "Automated Driving Systems".

While SAE level 1 vehicles feature a single Advanced Driver Assistance System (ADAS) –e.g., steering or accelerating–, SAE level 2 vehicles can control both steering and speed. The leap from SAE level 2 to SAE level 3 is substantial from a technological standpoint, but drivers should be clearly informed about how to use these vehicles. SAE level 3 vehicles have environmental sensing capabilities and can make informed decisions on their own to foresee some situations in which the system transfers control to the driver (hereinafter referred to as disengagement), but still require human takeover under some situations. The key difference between SAE level 3 and SAE level 4 is that the latter does not require the driver to intervene if the vehicle finds that it needs to release control. Therefore, SAE level 4 vehicles can operate in self-driving mode through road sections that meet some requirements.

Despite the great effort of the automotive industry during the last decade, the most advanced systems nowadays are SAE level 2 (SAE level 3 at the most). As mentioned above, these driving automation systems are not able to adapt to all circumstances that may arise throughout a road. An unexpected event may produce a disengagement, which could lead to an important weakness from a road safety perspective. This issue gets worse in safety terms as disengagements become less frequent; paradoxically, a system that generates fewer disengagements may have worse consequences from a road safety perspective. In contrast, drivers will probably switch off the system for their comfort on sections with very frequent disengagements. The frequency of disengagements depends on the system technology as well as the infrastructure and environment. In general, smoother road alignments tend to produce fewer transfers of control [6] [7] [8] [9] [10] [11].

To enable and promote a quick and reliable generalization of Automated Vehicles, users need to trust their capabilities. A driver should not voluntarily decide whether to connect the assistances, but rather by having objective information about its operation along the segment to be travelled. This information must be provided by combining the characteristics of the infrastructure and the driving automation system.

In addition to the development of automated vehicles, there is also a boost in making use of connectivity and information-sharing to further enhance traffic operation and safety [12]. *Vehicle to X* (V2X) refers to an intelligent transportation environment where all vehicles, users, and infrastructure systems are interconnected. Connecting all elements (vehicles, road users, infrastructure, traffic, weather data, etc.) will lead to a more accurate knowledge of traffic situation across the road network, which in turn will help improve traffic flow, reduce road crashes, and minimize vehicle emissions.

Besides communication between vehicles (V2V), connectivity between vehicles and infrastructure (V2I) comes into play. This protocol will allow vehicles to interpret traffic signals and know who has priority in certain critical situations. Likewise, CAVs will always be able to know the ideal route as they will know the status of traffic in real time thanks to Vehicle to Network (V2N) technologies. Furthermore, since they are not on their own, Vehicle to Pedestrian (V2P) communication is also being developed to alert the presence of pedestrians or cyclists. Different technologies are being developed and deployed such as Roadside Units (RSUs) equipped with DSRC/WAVE and ITS-G5 or Cellular V2X (C-V2X) solutions based on the last releases of 4G and/or 5G technology at some urban zones and along main highways.

Automated and connected driving goes hand in hand with different political objectives that the European Commission, the United States, the United Kingdom, and China has been pursuing for years. For this, new CAVs must be integrated into the transport system, requiring the joint work of all stakeholders. As a result, an adequate technical, legal, and political framework that promotes safer, more efficient, and sustainable mobility and automated driving is expected.

1.2. Objectives

This Special Project aims at analyzing the feasibility of a Smart Roads Classification (SRC) framework for the classification of the road infrastructure based on its physical characteristics, as well as on the reception capacity of the automation and connectivity of the vehicles. An integral road classification system would also allow an efficient planning of public investments on physical infrastructure, by enhancing operativity of driving automation, and on digital infrastructure, by increasing the benefits of connectivity between everything –including highways– and their users (V2X). Consequently, a safer and more comfortable road network is expected.

Given that the presence of CAVs is on the increase, it is necessary to develop a new Smart Roads Classification (SRC) system that facilitates users and vehicles performing on the roads correctly, using the driving automation systems. This information should range from indicating which road sections are not suitable for any type of automated driving, to sections that are ready for any automated system, going through various intermediate degrees depending on the CAV support. Additionally, the system should consider information about the connectivity capabilities.

The system should be based on existing automated driving technologies and be highly resilient in such a way that it can be quickly adapted to the technology progress, research findings, and best practices. Therefore, this should also be compatible with current road classifications and the existence of different proportions of non-automated vehicles and other user types. Moreover, the classification system should be universal (applicable to roads worldwide), and agreed upon, to enable a simple-to-use and rapid-to-implement tool. In this way, the SRC would allow road decision makers the planification and prioritization of investment needs in physical and digital infrastructure, including no-regret measures, to progressively expand and encourage an automated and connected driving.

Summarizing, an SRC should fulfill the following features:

- Safe, to increase safety levels by providing detailed information on the best automated driving in each smart road segment, at any given time.
- Common language, to facilitate communication between all stakeholders by using a standardized vocabulary and common ground.
- Useful, to facilitate the application and management by Road Administrations and Road Operators.
- Operational, to improve traffic operation for the higher smart levels.
- Sustainable, aiming at emission reductions for the higher smart levels.
- Universal framework, with compatible applications to roads worldwide and to all types of roads, considering different challenges and requirements faced by diverse countries.
- Standardized, to ease its development and implementation.
- Interoperable, to facilitate data exchange and sharing.
- Measurable, to define clearly the metrics used to define the Smart Road Levels.
- Robust, to provide an adequate, coherent, and stable Smart Level for each road segment, approaching a certifiable system.
- Dynamic, to reduce the assigned Smart Level after sudden variations in environmental and operational factors.
- Consistent, to facilitate adequate messages to users, both drivers and automated vehicles.
- Simple, to ensure understanding by users, both drivers and automated vehicles.
- Credible, to generate confidence in the user.
- Compatible, with all other non-automated vehicles sharing the smart roads.
- Integrable, to facilitate the necessary transition from the current classification systems.
- Flexible, to be quickly and easily adaptable to technological advances and sudden variations in technology operation.
- Fair Share of Responsibilities between all stakeholders, despite Road Administrators and Road Operators should estimate a proper Smart Road Level for all segments and maintain the segments to keep their Smart Level.

Nevertheless, all the objectives can be prioritized into different stages to easy the deployment of the Smart Roads Classification.

1.3. Scope

The Penetration Market Rate (PMR) of Connected and Automated Vehicles (CAVs) is increasing every year, so the development of a new road classification system based not only on traditional factors – economic-administrative and technical functionality, administrative ownership, morphology of the road, environment, and users–, but also on the particularities of this type of vehicles is needed to provide users accurate information about how ready the road is to support an automated driving. This information, from none to full readiness to automated driving, should be provided indicating different degrees of support. To determine the level of support, the Smart Roads Classification (SRC) system deals with diverse areas: (i) physical infrastructure, (ii) digital infrastructure, (iii) connectivity, and (iv) road users.

The classification level of a road may be displayed physically and/or digitally. Drivers may be informed by means of physical road signs (e.g., existing vertical ones but adapted) and the digital classification may also provide detailed information to driving automation systems (e.g., road geometry), for the levels that support this communication protocol. This information can be used by driving automation systems to determine their driving performance (e.g., actuated speed) and potential disengagement locations in advance.

As mentioned previously, the SRC is compatible with existing driving automation systems and resilient to their technological development so as to ensure an easy and quick adaptation to future changes. Likewise, it is a universal and standardized classification, pursuing a fast implementation by Road Administrations and Road Operators. Additionally, the system considers the coexistence between automated driving and non-automated driving as well as the presence of other road users. Nevertheless, it is important to note that the SRC is intended as an informative tool, not a commitment for Road Administrations and Road Operators.

This Special Project is not focused on defining the standards for the communication and information exchange between vehicles and infrastructures. Streets in urban areas are not covered, too.

2. METHODOLOGY

The development of this Special Project is divided into three main stages: (i) Data collection and analysis, (ii) Proposal of Smart Roads Classification (SRC), and (iii) Feasibility study of the SRC application (Figure 2).

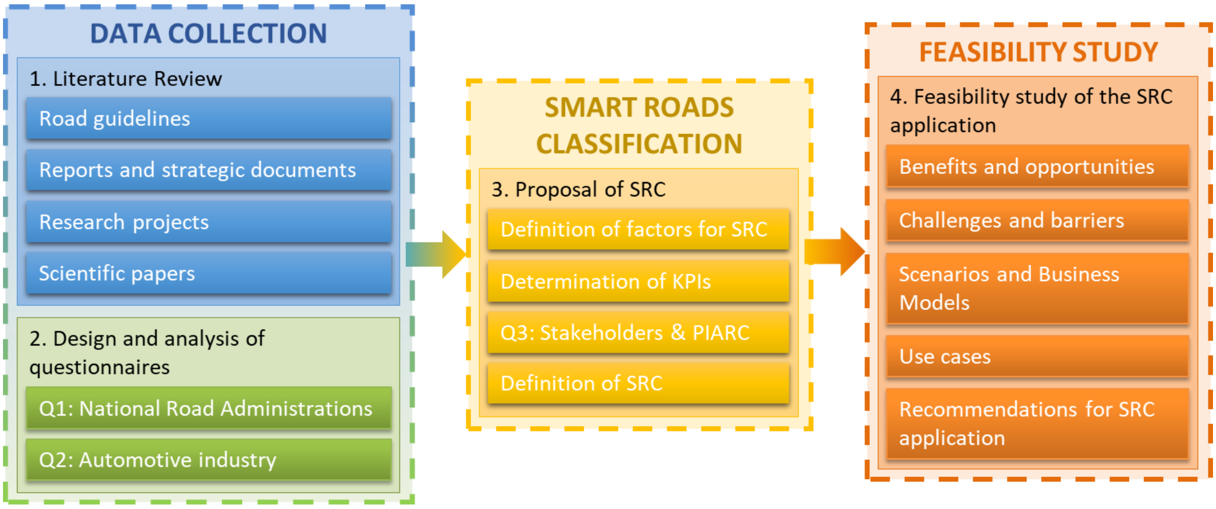


Figure 2. Methodology.

The data collection consisted of a world-wide literature review and the design and analysis of two questionnaires which were sent to Road Administrations (RAs) and Road Operators (ROs) and the automotive industry. The literature review was focused on information searches on the integration of connected and automated vehicles to current road classification systems and the limitations of the physical and digital infrastructure to expand the operation of current Connected and Automated Vehicles. The gathered information was structured in the following categories: (i) road guidelines, (ii) reports edited by road associations and administrations, (iii) research projects, (iv) reports and strategic documents, and (v) papers in relevant journals such as those in Journal Citation Reports. All these documents were analyzed to stablish the state of the art of automated driving from diverse perspectives: (i) impact of automated driving on road classification systems, (ii) current automated driving limitations, (iii) the role of connectivity in automated driving, (iv) key concepts linked to automated driving, and (v) the implications of automated driving on road safety.

The conclusions of the literature review were complemented with the findings obtained from the questionnaires to deal with the high level of uncertainty on the studied phenomenon. A first questionnaire (hereinafter Questionnaire 1) was sent to Road Administrations (RAs) and Road Operators (ROs) in developed and developing countries primarily to collect information about the current methods and procedures for road classification. To this regard, Questionnaire 1 included questions related to road network characteristics such as the length and percentage of each road category, type of road users, characteristics of road markings, pavement condition, type and allocation of traffic and environmental sensors, and current and future (planning) connectivity level of road infrastructure. These characteristics allowed determining how ready a country or region is to integrate Connected and Automated Vehicles and maximize their performance, and the corresponding investment needs. Additionally, RAs and ROs were also asked for the importance of different factors, grouped into diverse categories –physical infrastructure, digital infrastructure, connectivity, automation, and users–, in terms of the need to be integrated in the Smart Roads Classification system to ease and support the integration of CAVs.

The second questionnaire (hereinafter Questionnaire 2) was designed to be sent to the automotive industry (OEMs and TIER1s) so as to detect its main concerns and priorities regarding connected and automated driving and the needs and benefits for a new road classification. Descriptive and statistical analyses were carried out to study the data collected in Questionnaire 1 and 2.

On the basis of the conclusions of the literature review and the findings obtained from Questionnaire 1 and 2, a multilayer approach was proposed to deal with all different factors related to the road classification. These factors were defined and grouped into the following categories: (i) physical infrastructure, (ii) digital infrastructure, (iii) connectivity, and (iv) users. Due to the great interaction of the factors included in these categories, the proposed SRC was based on two main factors to ensure its practical application by RAs: automation readiness and connectivity support; expressed in terms of Level of Service for Automated Driving, (LOSAD) and Infrastructure Support Levels for Automated Driving (ISAD), respectively. Then, diverse Key Performance Indicators (KPIs) were proposed.

The preliminary version of the SRC was assessed by means of a third questionnaire (hereinafter Questionnaire 3) that was sent to all stakeholders: road and traffic authorities, road operators, road associations, vehicle manufacturers, sensors suppliers, BOT companies, academia, and members of the POT and PIARC Technical Committees. Additionally, two webinars were developed to disseminate the draft SRC proposal. The information gathered from all the stakeholders was then analyzed and considered for editing the final version of the SRC that included the needs, requirements, and recommendations from countries on all continents.

Finally, a feasibility study was developed to indicate how likely an SRC is to be applied. To do this, the benefits and opportunities of having an SRC were first identified. Afterwards, the challenges and barriers were determined. Then, plausible, future scenarios were presented, defining the role of each stakeholder. From these scenarios, different use cases were analyzed to show the applicability of an SRC. Regarding this, a specific study was conducted for the application of an SRC in Low-Medium Income Countries (LMIC). Last but not least, recommendations for a successful deployment of the SRC were also indicated for each stakeholder, including Road Administrations.

3. LITERATURE REVIEW

Automated driving can be analyzed from diverse perspectives as it is linked to manifold areas or fields. Particularly, this section aims at determining the impact of automated driving at the infrastructure level by covering the following issues: (i) impact of automated driving on road classification systems, (ii) current automated driving limitations, (iii) the role of connectivity in automated driving, (iv) key concepts linked to automated driving, and (v) the implications of automated driving on road safety.

First, an analysis of traditional and more sophisticated road classification systems is presented, including both road classifications only for human-driven vehicles and those that aims at integrating Connected and Automated Vehicles (CAVs). As a result, the main weaknesses of current road classification systems are identified.

Although vehicle technology is evolving very rapidly, the sensors and algorithms integrated in CAVs cannot deal with some demanding situations. To this regard, the second subsection defines the current influence of physical infrastructure on CAVs operation, grouped by the following attributes: (i) Road typology, (ii) Geometric design, (iii) Cross-section, (iv) Road markings, (v) Traffic signs, (vi) Junctions, (vii) Pavement condition, (viii) Road environment, (ix) Environmental conditions, (x) Vulnerable road users, (xi) Road works, (xii) Temporary emergency signage, and (xiii) Speed.

One of the most important challenges concerning automated driving is connectivity. The third subsection shows the different typologies of communication –(i) vehicle to vehicle short range, (ii) vehicle to infrastructure short range, and (iii) vehicle to infrastructure medium/long range– and how connectivity can benefit CAVs performance, especially to achieve a high-level automation.

The fourth subsection summarizes the impact of connected and automated vehicles on road safety. Regarding this, the implications of automated driving on safety are analyzed at diverse levels –(i) vehicle, (ii) transportation system, and (iii) society– and quantified by means of different approaches –(i) target crash population, (ii) road test data analysis, (ii) traffic simulations, (iii) driving simulators, (iv) system failure risk assessment, and (vi) CAV safety effectiveness–.

Finally, in the last subsection, a summary of the main findings and conclusions is included.

3.1. Road Classifications

Most of the previous road classification systems were designed for conventional motorized vehicles, i.e., for human drivers. Only a few recent classification systems consider the advent of Connected and Automated Vehicles (CAVs).

3.1.1. Road Classifications for Human-driven Vehicles

The traditional Functional Classification System (FCS) considers the road to be strictly a transportation corridor for motorized vehicles [13] [14]. The FCS has been used for decades by transportation planners as a method of communicating the road's character of service [15]. In its most basic form, the FCS is based on two fundamental opposite dimensions: mobility and accessibility. While these two dimensions lie at opposite ends of the continuum of roadway function, most roads provide some combination of each, ensuring a proper road safety level [16]:

- **Roadway mobility** function provides a few opportunities for entry and exit and therefore low travel friction from vehicle access/egress.

- **Roadway accessibility** function provides many opportunities for entry and exit, which creates potentially higher friction from vehicle access/egress.

In addition to mobility and accessibility, there are other important factors related to the functional classification: (i) efficiency of travel, i.e., shortest travel time, (ii) collectors, (iii) access points, (iv) speed limit, (v) route spacing, (vi) usage –Annual Average Daily Traffic (AADT) Volumes and Vehicle Miles of Travel–, (vii) number of travel lanes, and (viii) regional and statewide significance [16].

Regardless the type or reason of the trip, the following stages can be usually identified along an itinerary which refer to the hierarchy of motor vehicle movements [2]:

- Main movement.
- Transition.
- Distribution.
- Collection.
- Terminal access.

Each of the six stages of a typical trip is handled by a separate facility designed specifically for its function. Because the movement hierarchy is based on the total amount of traffic volume, freeway travel is generally highest in the movement hierarchy, followed by distributor arterial travel, which is in turn higher in the movement hierarchy than travel on collectors and local access routes. This results in the conventional system consisted of arterial, collector, and local roads. Although the concept of these road types could vary among countries or regions, a widely accepted definition of the three terms is as follows [2]:

- **Arterials** serve a primary function of vehicle mobility, generally for longer trips at a more regional scale.
- **Collectors** serve a balance of regional and local trips and function, especially as transitions between local access streets and arterial mobility streets.
- **Locals** are oriented primarily toward access. As a rule, they tend to be designed for lower speeds and often (though not always) a more limited range of vehicles.

In this way, local roads mainly provide accessibility, arterials boost mobility, and collectors offer an intermediate solution between previous ones.

Since its inception, this classification system has evolved with the intention of adapting to the new circumstances of society. This is the case of the proposed classification system of the Interurban Roads Technical Committee of the Spanish National Committee of PIARC (ATC) [1], which included as main factors the economic-administrative functionality, the administrative ownership (e.g., national, state, regional, provincial, and local), the technical functionality (e.g., arterial, collector, and local), the morphology of the road (e.g., freeway, multilane, and two-lane rural road), and the environment (e.g., rural, suburban, and urban).

The **Expanded Functional Classification System** [2], proposed recently in the United States, integrates the different types of users. Specifically, this classification system combines two of the criteria defined by the ATC Committee –environment and technical functionality– with the type of user.

Environment is considered in the Expanded FCS as ***Roadway Context***. To this regard, three primary factors are used to define this factor:

- Density, that is related to the existence and types of structures.

- Land use, that includes residential, commercial, industrial, and agricultural uses.
- Building setback, that refers to the distance of structures to adjacent roadways.

Table 1 summarizes the different roadway context categories.

Category	Density	Land use	Setback
Rural	Lowest	Agricultural	Usually large setbacks
Rural Town	Low to medium	Primarily commercial	On-street parking and sidewalks
Suburban	Low to medium	Mixed residential and commercial	Varied setbacks
Urban	High	Mixed residential and commercial	On-street parking and sidewalks
Urban Core	Highest	Mixed commercial, residential, and institutional	Small setbacks

Table 1. Roadway Context categories [2].

Moreover, technical functionality is referred as ***Roadway Type***. Particularly, this criterion uses existing roadway type names so as to ease its understanding and preserve consistency with other uses of functional classification categories. In this way, a total of five roadway type categories (Table 2) are defined considering the following factors:

- Network importance, that depends on the national, regional, and local importance of the roadway.
- Connected areas, that is related to the types of activity centers and locales that are connected by the roadway.

Category	Network importance	Typical Uses
Interstates, Freeways, and Expressways	National corridors providing long distance travel	• Limited access • Through traffic movements • Primary freight routes • No pedestrian or bike traffic
Principal Arterial	Regional corridors connecting large centers of activity	• Through traffic movements • Longer distance traffic movements • Long haul public transit buses • Primary freight routes
Minor Arterial	Local corridors connecting centers of activity	• Connections between local areas and network principal arterials • Connections for through traffic between arterial roads • Access to public transit and through movements • Pedestrian and bike movements

Collector	Roadways providing connections between arterials and local roads	• Carry traffic with trips ending in a specific area • Access to commercial and residential centers • Access to public transportation • Pedestrian and bicycle movements
Local	All other roads	• Direct property access – residential and commercial • Pedestrian and bicycle movements

Table 2. Roadway type categories [2].

Finally, the third main factor of the Expanded FCS is ***Vehicular Roadway Type*** which is associated with road users. In this context, three categories of users are considered: drivers, bicyclists, and pedestrians. The level of modal priority on the corridor is defined as High, Medium, or Low (represented by icon size in Figure 3) based on the importance of the link to the individual mode system, as well as to existing or potential demand on the corridor. The correlation of context and roadway types and overlays results in the functional classification matrix that allows the development of a context-based multimodal design (Figure 3).

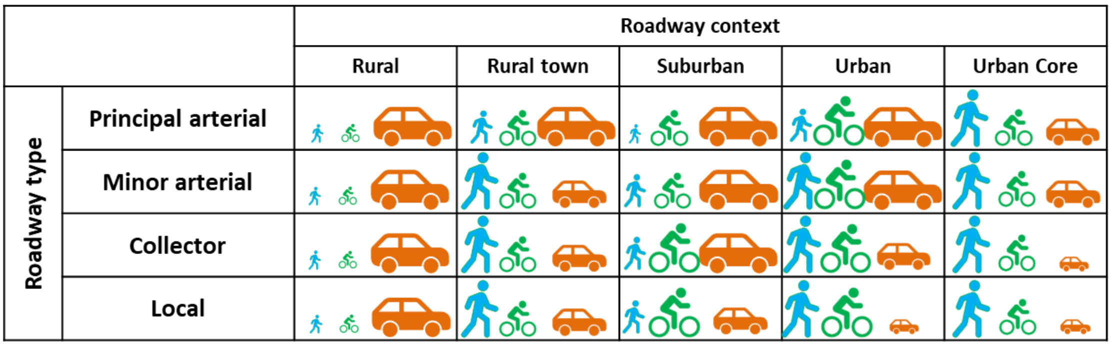


Figure 3. Expanded Functional Classification System. Adapted from [2].

3.1.2. Road Classifications for Connected and Automated Vehicles

However, none of the previous classification systems considers the incipient appearance of Connected and Automated Vehicles (CAVs) on our roads. In this context, two research projects have recently finished integrating the particularities of CAVs in road classification: Connected Roadway Classification System [3] and INFRAMIX [4].

The **Connected Roadway Classification System** (CRCS) established a road classification system based on three approaches: (i) talking, (ii) seeing, and (iii) simplifying. Talking refers to connectivity between vehicles and infrastructure. This approach is independent of the technology. Two current technologies are DSRC using the 5.9 GHz bandwidth and cellular communication, often identified as C-V2X. An Infrastructure Owner/Operator (IOO) would deploy and construct communication systems that would allow for V2V and V2I. Regarding seeing, improvements in the infrastructure can enhance the performance and accuracy of sensors on CAVs –e.g., radar, cameras, and LIDAR–. Some examples are related to changes in the shape, size, or materials of signs, pavement markings, and traffic signal control systems. Finally, simplifying refers to adjust the roadway geometric design to simplify CAVs operation. This approach includes changing usage or user access, changing roadway control, or modifying the alignment or cross section to improve CAVs safety and performance.

As a result, four road levels are proposed depending on the degree to which the road allows an automated driving:

i. Need of upgrade and maintenance: Design or functionality that falls short of meeting existing guidance or recommendations for future technology accommodation.
ii. Meets current best practices: Design or functionality that meets existing guidance or recommendations for future technology accommodation.
iii. Meets emerging markets (1-5 years): Design or functionality that supports early adoption of Connected and Automated Vehicle (CAV) applications or positions the roadway elements for communication/interaction with vehicles.
iv. Meets next decade market (10 years): Design or functionality that supports operation of most CAV applications and/or communicates/interacts with vehicles proactively.

However, some issues included in the classification are still unknown, i.e., further research is required to establish more clearly some of the criteria on which this classification system is based. Figure 4 represents these research needs by traffic lights, from green, that means there is significant knowledge and certainty, to red, that means that significant uncertainty exists.

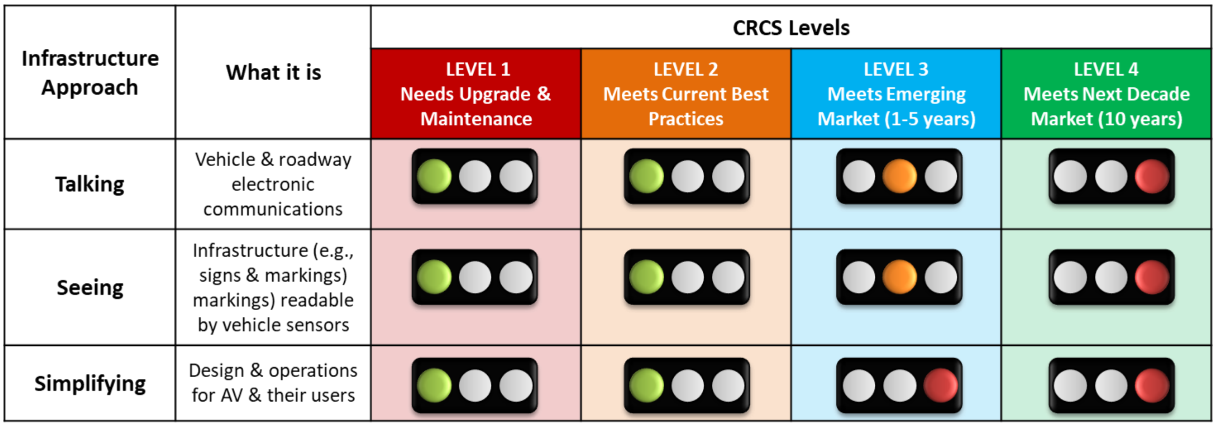


Figure 4. Connected Roadway Classification System. Research needs. Adapted from [3].

Table 3, Table 4, and Table 5 present the proposed infrastructure approaches, classification levels, and criteria within these levels for the CRCS.

Infrastructure approach	Infrastructure element	CRCS Assessment Levels			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Talking	Roadway	No wireline or wireless communication ability	Fiber communication along roadway. Good cellular coverage in corridor	DSRC or C-V2X nodes tied into fiber backbone	Small cells deployed in roadway right-of-way with good 5G coverage and connection to fiber backbone
	Traffic signals	Signal meets MUTCD but internal technology is outdated	Signal meets MUTCD and is a current technology. Signal is part of a connected system	Signal is equipped with V2I communication capability	Signal transmits SPaT messages
	Roadside devices	No or limited roadside devices with no communication capability	ITS equipment is tied to fiber backbone or have cellular capability to communicate to TMC	Infrastructure element is also equipped with capability to communicate over DSRC or C-V2X	Infrastructure element communicates information on conditions and performance with local processing capability

	Temporary traffic control devices	Traffic control devices are deployed with no communication capability	Temporary traffic control devices are equipped with cellular communication capability	Portable infrastructure element is equipped with technology that has the capability to communicate	Portable infrastructure element communicates information on conditions and performance

Table 3. Connected Roadway Classification System. Criteria for Talking [3].

Infrastructure approach	Infrastructure element	CRCS Assessment Levels			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Seeing	Roadway	Roadway assets are not recorded in digital form	Digital inventory of roadway assets exists	Major corridors or areas have digital maps	All roadways are digitally mapped
	Signs	Signs may not be present or if they are present may lack desired visibility	Signs meet desired visibility	Signs provide visibility needed for CAVs recognition	Signs include technology that provide for future machine visibility and processing
	Marking	Markings may not be present or if they are present may lack desired visibility	Markings meet desired visibility	Markings are present and consistent and provide visibility needed for CAVs recognition	Markings include technology that provide for future machine visibility and processing
	Traffic signals	Traffic signals are in need of upgrade or maintenance	Traffic signal equipment meets MUTCD requirements	Signal heads are consistent in design and use of technology	Research is needed

Table 4. Connected Roadway Classification System. Criteria for Seeing [3].

Infrastructure approach	Infrastructure element	CRCS Assessment Levels			
		Needs Upgrade & Maintenance	Meets Current Best Practices	Meets Emerging Market (1-5 years)	Meets Next Decade Market (10 years)
Simplify	Roadway	Infrastructure geometry may not meet AASHTO guidelines and/or pavement in poor condition	Infrastructure geometry meets AASHTO guidelines and there are no pavement defects	Infrastructure geometry is designed to facilitate CAVs performance	Infrastructure geometry is specifically designed to accommodate CAVs navigation and operation
	Temporary roadway geometry	Minimal navigational aids are available to defined temporary geometry	Navigational aids for temporary geometry are in compliance with the MUTCD	Navigational aids for temporary geometry are in compliance with the MUTCD and are equipped with communication technology and are designed to be visible for CAVs	Navigational aids for temporary geometric changes communicate with vehicles and are designed to support CAV navigation and operations
	Low-speed environments	No designation of zona or district for CAVs	Infrastructure geometry meets design guidance and traffic control devices meet MUTCD	Research is needed	Research is needed
	Dedicated facilities	No designation for a dedicated CAV facility	Managed lanes that have user requirements for access	Research is needed	Research is needed

Table 5. Connected Roadway Classification System. Criteria for Simplifying [3].

One of the most valuable contribution of this project is its application. The CRCS was developed to be flexible enough to accommodate diverse needs and uses. This classification can be used for (i) determining the degree to which a road network allows an automated driving, (ii) programming investments to encourage a higher CRCS level, and (iii) ranking the Infrastructure Owners/Operators (IOO) in terms of the maturity of their roads.

The IOO might act on one or more of the infrastructure approaches. Regarding this, the Colorado Department of Transportation (CDOT) previously proposed a road classification system consisting of six levels based on the roadway's ability to support operations, ITS, and CAVs. These levels are summarized as follows:

- Level 1: Unpaved and/or non-striped roads are designed to a minimum level of standard of safety and mobility.
- Level 2: Paved roads are designed to the AASHTO guidance and pavement markings and signing meeting the MUTCD standards. ITS equipment or infrastructure is not available to collect connected vehicle data. Access to cellular data service may be available.
- Level 3: There is ITS equipment operated by a Traffic Operation Center (TOC), one-way electronic data share between DOT/vehicle/user, and/or mixed-use lanes.
- Level 4: Roadway or specific lane has adaptive ITS equipment (i.e., smart signals hold for vehicles, highway lighting turns on for vehicles, etc.) with TOC override only; two-way data share exists between DOT/vehicle/user; and/or lanes are designated for vehicle Levels 3 and 4 only.
- Level 5: (Advance guideway system) roadway or specific lane is designed for vehicle Level 4 only with additional features that may include inductive charging, advanced/enhanced data sharing, and so forth. No roadside signs are needed since all roadway information is direct to vehicles' on-board systems.
- Level 6: All lanes on the roadway are designed for only SAE level 4 vehicle systems –no signs, signals, striping needed–.

These levels can relate to CRCS as shown in Table 6. In this way, the CRCS framework would support CDOT in continuing to use its definitions but further expand its levels across the infrastructure approaches.

	CRCS Assessment Levels			
Infrastructure Approach	**Needs Upgrade & Maintenance**	**Meets Current Best Practices**	**Meets Emerging Market (1-5 years)**	**Meets Next Decade Market (10 years)**
Talking	CDOT Level 1	CDOT Level 2	CDOT Level 4	CDOT Level 5-6
Seeing	CDOT Level 1	CDOT Level 2-3	CDOT Level 4	CDOT Level 5-6
Simplifying	CDOT Level 1	CDOT Level 2	CDOT Level 4	CDOT Level 5-6

Table 6. CDOT classification system in CRCS Framework. Adapted from [3].

As a flexible tool, the CRCS need to be maintained. The framework must be updated as the capabilities of CAVs evolve. Given that the uncertainty in a 10-year horizon, the next revision of this framework is expected to be before 2025. This task should definitely be conducted by all stakeholders –IOOs, automotive groups, standards groups (e.g., SAE), research groups, and cross-cutting groups (e.g., ITS America)–. Gaining acceptance and encouraging use of the CRCS is key to aligning implementation of the infrastructure with the needs of CAVs.

The main goal of the **INFRAMIX project** [4] [17] was to prepare the road infrastructure to accommodate the introduction of CAVs. One of its most important outcomes was a road classification scheme which considered how road facilities supported V2I connectivity. This classification was organized as a set of five levels, entitled *Infrastructure Support Levels for Automated Driving (ISAD)*. These levels were based on the idea of the SAE levels, but both concepts are independent. Depending on the compliance of the different characteristics shown in Table 7, the ISAD levels are described – from lowest to highest connectivity performance– as follows:

- ISAD level E refers to a conventional infrastructure, with no digital information provided to vehicles. Thus, automated driving is only possible if the vehicle is able to fully recognize road geometry and the environment, including road signs, etc.
- ISAD level D includes support for static information (e.g., basic road geometry, road signs, etc.), which could be used by vehicles –especially the lowest SAE levels– to complement and check the on-site information. Dynamic information, such as traffic lights, road works, and Variable Message Signs are not supported and should be detected by the vehicle. It should be highlighted that dynamic signs are those which are more difficult to be read by driving automation systems [5]. This level requires sporadic connectivity to databases.
- ISAD level C adds support for these dynamic signs, as well as work zones, warnings, incidents, weather, etc. This level adds very valuable information for Automated Vehicles (AVs), which could use this information to inform drivers to take informed decisions about navigation or driving. This level requires regular updates from maps and databases (i.e., a few seconds).
- ISAD level B presents a huge leap forward from previous levels. Using physical- or digital-based information, the infrastructure is capable of collecting and interpreting traffic situations, delivering back it to vehicles. This level and level A require a very high frequency exchange of information from/to vehicles (i.e., milliseconds).
- ISAD level A is the top level, in which the infrastructure is able to collect and transmit microscopic traffic information. This level needs full connection with vehicles to retrieve exact traffic conditions, as well as to communicate advices on speed, lane usage, lane change recommendations, etc. A dramatic optimization of the traffic performance is expected in this level [5].

Level and Name		Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
A	Cooperative driving	X	X	X	X
B	Cooperative perception	X	X	X	
C	Dynamic digital information	X	X		
D	Static digital information / Map support	X			
E	Conventional infrastructure / no AV support				

Table 7. Characteristics of the different ISAD levels [17].

The ISAD levels have supposed a very important contribution to the CAV environment. With it, road itineraries could be planned and suggested considering the ISAD level of the different road facilities (road segments and junctions). Specific protocols and facilities are still being tested, focusing on how different management strategies and road infrastructure elements would perform with mixed traffic. In addition, this classification system could be used to prioritize actions towards enhancing road connectivity, prioritizing investments to enhance the ISAD level of sections showing the highest benefits.

More recently, the **European Asphalt Pavement Association** (EAPA) proposed a classification of roads –or stretches of these– which aimed at providing, in a simple way, information to the driver and/or vehicle about the available technologies supporting the automated and electrified driving [18]. This classification is the result of the combination of the following approaches: (i) Infrastructure Support levels for Automated Driving (ISAD) defined in INFRAMIX (see Table 7), (ii) levels of driving automation defined by the Society of Automotive Engineers [5], and (iii) Electric Road Systems (ERS) –inductive, conductive catenary overhead, and conductive in-road rail– discussed by the World Road Association [19].

Based on these approaches, the EAPA defined six classes of roads –from A to E– for adopting connected and automated vehicles, followed by a number of stars –from 0 to 3 stars– that indicates the technologies available to charge electric vehicles (Table 8 and Table 9). As an example, a driver accessing a road with class B ★★ knows that, along this, the vehicle is effectively communicating with the infrastructure. Therefore, the vehicle can operate even under low-visibility conditions and all dangerous sections are foreseen and avoided. In addition, in case that the automated system cannot address any dangerous situation, the vehicle can stop, out of the lane, until the driver retakes control.

ISAD	SAE Driving Automation					
	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
E	F	E	E	E	E	E
D	F	E	D	D	D	D
C	F	E	D	C	C	C
B	F	E	D	C	B	B
A	F	E	D	C	B	A

Table 8. EAPA classification of roads according to the level of readiness for adopting connected and automated vehicles.

Class	Description
-	No equipment
★	Charging systems only for certain conditioned vehicles
★★	Static systems to charge any vehicle while stopped in specific areas
★★★	Dynamic systems to supply energy to any vehicle circulating along the road

Table 9. EAPA classification of roads according to the level of readiness for adopting electric vehicles.

Table 10 summarizes the key parameters necessary to identify the class of a road or stretch.

Class	Key parameters
F	• Optical visibility not clear in at least 100 m • Deficient or non-existing markings, signs, and traffic lights • State of pavement: Inadequate
E	• Optical visibility clear in 50 m • Existence of marking, signs, and traffic lights in good condition and clearly visible • State of pavement: Adequate
D	• Optical visibility clear in 100 m • Existence of marking, signs, and traffic lights in good condition and clearly visible • Digital information about road geometry and static signs available • State of pavement: Satisfactory
C	• All static and dynamic infrastructure information available in digital form • Assisted visibility systems • State of pavement: Excellent • V2I communication systems • Emergency parking lane • Construction/maintenance works updated in geophysical system • Real-time data detection systems
B	• *Key parameters for Class C* • Real-time microscopic traffic situations detection systems
A	• *Key parameters for Class B* • Integral vehicles management system

Table 10. Key parameters proposed by EAPA for each road class.

According to the EAPA, Road Administrations and Authorities can refer to this classification to determine the necessary actions to be implemented to make possible vehicles' operation under a specific level of automation and electrification.

Finally, it is worth to note the **Autonomous Vehicles Readiness Index** (AVRI) proposed by KPMG International to assess the preparedness of 30 countries and jurisdictions to facilitate an automated driving [20]. Despite that this approach is not actually a road classification system, it includes some measures and factors that could be worth for road classifying. Moreover, the ranking of countries could guide the application of the new Smart Roads Classification in a short and medium-term.

This index consists of a total of 28 individual measures gathered into four pillars:

- Policy and legislation.
- Technology and innovation.
- Infrastructure.
- Consumer acceptance.

The variables under the four pillars are combined to arrive at an aggregate score for each. Variables are given equal weight in arriving at the overall pillar score, with the exception of the mobile connection speed and broadband measures in the infrastructure pillar which both have half the weight of other measures to arrive at an overall score for this particular area. Before the data is combined it is normalized, as the variables have different measurement units, using the min-max method. This converts the variables to a range between zero and one, by subtracting the minimum value and dividing by the range of the variable values. Therefore, the top-ranked country receives one and the bottom country zero. Pillars have differing number of variables, so each pillar score is scaled to give them the same maximum possible value. This means that each pillar has equal weight in the overall score for each country and jurisdiction.

Table 11 presents the different variables that are associated to each pillar. According to the 2020 ranking, Singapore leads the Policy and legislation pillar, gaining the top scores on five of its seven measures. Related to this, the UK retains its second place on this pillar and leads on the measure assessing the data-sharing environment. On the other hand, Israel leads the Technology and innovation pillar, reaching the greatest score for AV technology firm headquarters and investments in AV-related firms. In the same pillar, the US leads on industry partnerships and the assessment of cloud computing whereas Japan presents the highest score on AV-related patents. Concerning the Infrastructure pillar, the Netherlands continues to be the clear leader with very high scores on EV charging stations and road quality. South Korea is second and leads on the measure related to 4G coverage. Finally, Singapore also presents the greatest score in Consumer acceptance pillar, whereas three Nordic countries –Finland, Sweden, and Norway– are in the top 5.

Pillar	Measures
Policy and legislation	• AV regulations • Government-funded AV pilots • AV-focused agency • Government readiness for change • Future orientation of government • Efficiency of the legal system in challenging regulations • Data-sharing environment
Technology and innovation	• Industry partnerships • AV technology firm headquarters • AV-related patents • Industry investments in AV • Availability of the latest technologies • Innovation capability • Cybersecurity • Assessment of cloud computing, AI and IoT • Market share of electric cars
Infrastructure	• EV charging stations • 4G coverage • Quality of roads • Technology infrastructure change readiness • Mobile connection speed • Broadband
Consumer acceptance	• Population living near test areas • Civil society technology use • Consumer ICT adoption • Digital skills • Individual readiness • Online ride-hailing market penetration

Table 11. Autonomous Vehicles Readiness Index: Pillars and Measures. Source: KPMG International.

Figure 5 shows the AVRI rankings from 2018 to 2020.

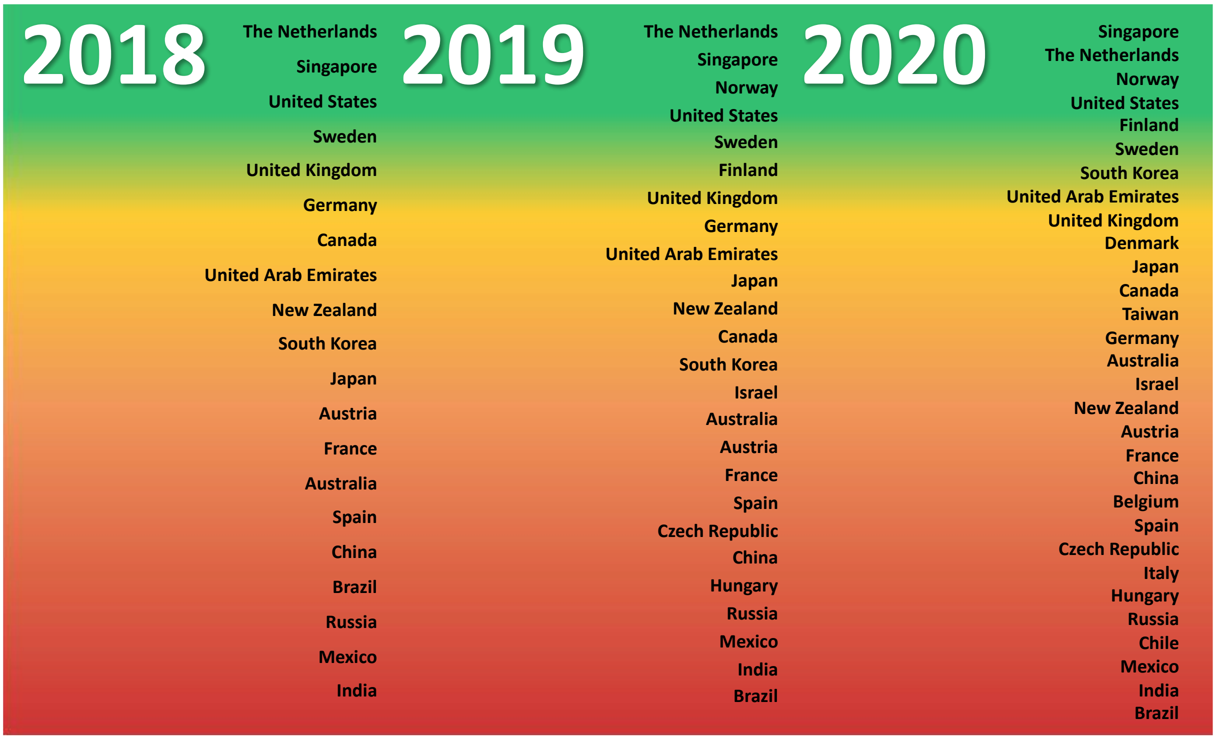


Figure 5. AVRI rankings from 2018 to 2020. Source: KPMG International.

3.1.3. Shortcomings of Existing Road Classification Systems

First approaches on road classification systems were focused on motorized vehicles driven by humans. In the last decade, some highway administrations have incorporated vulnerable users, such as cyclists and pedestrians, in the classification of the road network. However, this is not enough as automated vehicles already are a reality in our roads.

To address the integration of CAVs in road classification systems, some efforts have been carried out in the last years that include different approaches [3] [17] [18] [20]. The CRCS, based on three main approaches –talking, seeing, and simplifying– can be very practical for road administrations and operators to allocate investments, but not for road users as the classification system does not stablish clear road levels [3]. To this regard, the proposed classification system defines the attributes or conditions to be gathered in each road level but does not specify the key performance indexes for these attributes. Therefore, the application of the system requires of further development.

The ISAD levels proposed in the INFRAMIX project [17] add a critical aspect for automation –especially the highest levels–. However, connectivity is not sufficient on its own to define how ready a road section is to host automation. For instance, smooth alignments with weak connectivity are likely to be more drivable by automated vehicles than low-end ones with magnificent connectivity conditions.

Despite the benefits, these levels still require to be completed with additional information to be fully adopted by road authorities and/or operators. This information includes, but it is not limited to, the accuracy of the maps at the different levels, the update rate of the static information, communication capacity and protocols to/from vehicles, etc.

The classification system proposed by the EAPA [18] relies on connectivity and vehicle capabilities. In this way, six road classes are defined depending on the ISAD levels [17] and SAE levels of automation

[5]. Additionally, the classes are complemented with a number of stars that indicates the integration of electric vehicles. Despite the inclusion of some key parameters associated with the infrastructure –road marking, signs, and pavement condition–, other important factors –e.g., road geometric design– are not considered. Thus, this classification system underestimates some essential factors that has a great impact on CAVs performance.

Finally, the Autonomous Vehicles Readiness Index (AVRI) includes issues or items not considered by the previous systems such as *Consumer acceptance* and *Policies and regulations* [20]. These items together with *Infrastructure* and *Technology and innovation* are the four pillars that define the level of automation of a country at a macro level. This index cannot properly reflect the degree to which a road network is enabling an automated driving because of its definition. In fact, the infrastructure pillar is mainly based on items related to connectivity, disregarding physical infrastructure features.

In short, the proposed classification systems integrating CAV particularities are based on diverse approaches and, therefore, a harmonization is needed. Although policies and regulations are needed to boost the use of CAVs and consumer acceptance is crucial to increase CAV sales, the level of automation of a road must not depend on these issues. On the other hand, most of criteria included in existing classification systems are not associated with Key Performance Indexes, making the implementation of these systems harder. Last but not least, none of the existing systems integrate dynamic conditions of the road –e.g., traffic volume or weather conditions– to determine the capability that a road has to enable an automated driving.

3.2. AUTOMATED DRIVING LIMITATIONS

This section presents the impact of the physical infrastructure on the automation capabilities of Connected and Automated Vehicles (CAVs). In particular, the following attributes or factors are discussed: (i) Road typology, (ii) Geometric design, (iii) Cross-section, (iv) Road markings, (v) Traffic signs, (vi) Junctions, (vii) Pavement condition, (viii) Road environment, (ix) Environmental conditions, (x) Vulnerable road users, (xi) Road works, (xii) Temporary emergency signage, and (xiii) Speed.

3.2.1. Road typology

The capacity of a road infrastructure is used to define its efficiency [21]. On highways, this factor depends on the maximum possible flow of traffic on the road sections as well as the specific capacity of entry, merging, and exit lanes. In contrast, the capacity on urban and suburban roads mainly depends on the capacities at intersections.

In this context, the capacity of a road infrastructure will change with CAVs penetration. With a purely autonomous traffic, the capacity is expected to increase about 40% and 80% in cities and on highways, respectively [21]. The difference between these values is due to the average speed at which vehicles drive when traveling along the road infrastructure. However, this increased traffic capacity will likely lead to an overuse of the infrastructure, causing a premature damage in the early service lifetime.

Although the influence of CAVs on road infrastructure capacity is clear, the figures presented above will be achieved as long as CAVs can drive in an automated way. To this regard, CAVs performance depends mainly on the type of road. While high-capacity roads –freeways, expressways, and motorways– are already ready to integrate CAVs as their features encourage road readability and connectivity, two-lane rural roads and urban roads are characterized by more demanding features (e.g., geometric design, traffic management, and heterogeneous traffic). In addition, high-capacity roads with separated carriageways ease the development of specific tasks –e.g., the overtaking maneuver–.

Johnson [22] highlighted the need not only of the preservation of the current roads for lower levels of automation, but also the construction of new or additional infrastructure for higher levels of automation. One example of that is the creation of dedicated lanes (DLs) –lane used only for CAVs– [23]. However, the construction of DLs might require the design and construction of additional elements such as tunnels, bridges, and specific entry and exit ramps [24]. The safety impact of these lanes was studied by Yu et al. [25]. When the dedicated lane was deployed on the innermost lane, efficiency improved for any market penetration rates, whereas safety improved only for low penetration rates.

A conceptual framework accounting for the factors that could affect the safety and efficiency of DLs was proposed by Rad et al. [26]. The presence of CAVs could influence drivers' behavior of human-driven vehicles. Such effects include shorter time headways and gaps that drivers of human-driven vehicles may adopt in car following and lane changing maneuvers, respectively. This can influence traffic efficiency and safety. DLs with physical separation from the normal lanes arise to minimize the negative effects of behavioral adaptations of drivers of human-driven vehicles and, consequently, increase safety. According to Rad et al. [26], a key factor affecting this phenomenon is the market penetration rate.

Additionally, the research needs concerning DLs were identified and prioritized as follows: (i) to specify the types of vehicles that can drive on DLs, (ii) to incorporate existing algorithms of CAVs in both driving simulator experiments and microscopic simulation, (iii) to translate the empirical data regarding human behavioral adaptation observed from field tests and driving simulator studies to mathematical models and implement them in traffic flow simulation platform. In addition to this, it is also suggested the development of automated lane change algorithms.

Another approach in urban environment is based on the concept of self-organization, i.e., there would be no lanes, no curbs, no delineation, and no regulation. Although this approach is a more challenging scenario for CAVs, city centers have already been identified as possible CAV-only areas [27].

Finally, McDonald and Rodier [28] stablished several aspects by which CAVs will influence road infrastructure. Among these aspects, the changes coming from CAVs will require a reclassification of motorways and a change in design-related standards. In this context, the authors propose high-speed dedicated lanes on motorways in combination with reserved exit ramps.

3.2.2. Geometric design

Some research studies have been developed to analyze the influence of road geometric design on CAVs performance [7] [8] [29] [30] [31] [32]. Mainly, the most critical situations are located at sharp horizontal curves and crest vertical curves as the visibility of the vision cameras installed in the vehicles is limited.

On the one hand, García et al. [7] proposed a new speed concept, automated speed, as the maximum speed that an automated vehicle can achieved at a specific road element. In this way, García et al. analyzed the automated speed that a SAE level 2 vehicle can travel along horizontal curves. As a result, this speed increased as road curvature decreased. For sharp-to-medium curves (radii lower than 450 m), the automated speed was found to be well below design and operating speeds. A lower automated speed would result in a) vehicles operating at a lower speed that a human driver would, or b) vehicles disengaging at a variable number of curves. Therefore, the current driving automation systems can operate along high-end freeways but cannot on most two-lane rural roads.

Another important factor related to this phenomenon is the use and type of transitions curves. The algorithms included in CAVs to keep the vehicle in the lane aims at predicting road curvature [29] [30] [31]. However, the type and use of transition curves differ among regions or countries which makes difficult the application of these algorithms. Indeed, García et al. [7] identified different automated speeds at various horizontal curves depending on travel direction. This fact was due to either the different features of the adjacent transition curves or sudden changes in curvature –i.e., horizontal curves without transition curves–.

On the other hand, García et al. [8] identified that sharp crest vertical curves can produce disengagements in CAVs, transferring vehicle control to the driver. To avoid the influence of the horizontal alignment, the studied crest vertical curves were overlapped with tangents. As a result, García et al. found that those crest vertical curves with a *K* lower than 20 m/% led to a manual driving experience, i.e., the vehicle system could not travel along the vertical curve in an automated way. Additionally, the automated speed was higher than the design speed for values of *K* higher than 10 m/% which brings to light the importance of considering operating speed instead of design speed for the performance of the automation system.

Finally, another aspect to be considered related to geometric design is visibility. To this regard, current road guidelines were stablished in base of the point of view of human drivers, i.e., ensuring its visibility. However, vehicle sensors that have to read the road –i.e., replacing human drivers– are installed at different heights which significantly influence object and road marking detection [8]. A particular case of visibility reduction is caused by truck platoons on horizonal curves of highways with, at least, two lanes in the same direction (freeways, motorways, and multilane roads). Reduced gaps between trucks travelling in a platoon will heavily reduce visibility in overpassing maneuvers [32]. Compared to human-driven cars, CAVs might benefit from lower perception-reaction times, but radar's characteristics such as its range and cone of visibility might cause additional determinants of visibility. Regarding radar range, a minimum of 170-180 m and short perception-reaction times are required so that radar does not further condition visibility [32]. Regarding cone of visibility, only angles greater than 20 centesimal degrees ensure that the radar does not condition visibility at all [32]. Technology might already be capable of achieving these characteristics, but most manufacturers do not share nor confirm this kind of data. This is the reason why tests should be carried out in order to ensure safety is guaranteed. In any case, the fact that radar characteristics do not condition visibility does not mean that the effect of truck platoons on visibility is avoided. Therefore, solutions which could involve additional countermeasures in the field of CAVs have still to be proposed and implemented [32].

3.2.3. Cross-section

Lane width, type and width of shoulders, and median configuration also have an important impact on Connected and Automated Vehicles. Although some research [33] [34] [35] pointed out the possibility of reducing lane width as lane-related vehicle systems –Lane Departure Warning (LDW), Lane Keeping Assist (LKA), and Lane Centering Assist (LCA)– will ensure the vehicle travel centered in the lane, current vehicle systems tend to fail on narrow lanes. To this regard, García et al. [9] found that a human control was always needed when lane width is lower than 2.5 m. Likewise, from a 2.75 m lane width an automated driving experience was observed. Finally, a lane width of 2.72 m was defined as "critical lane width" as it had the same probability of automatic and human lateral control.

Moreover, Scanlon et al. [36] analyzed the impact of LDW and LKA on road safety. The study concluded that lane-related vehicle systems help avoiding crashes as long as the road is equipped with lane markings and expanded shoulders (i.e., shoulder width of 3.6 m). When only shoulder widths were expanded, LDW could prevent 50%-54% of crashes and 44%-48% of seriously injured drivers.

Due to the reduction of visibility caused by truck platoons with shorter gaps on horizontal curves for vehicles overpassing them, lane width should not be reduced to allow some margin of platooning lateral position to increase sight distance [32]. Moreover, thanks to the automated systems for lane centering, there will be a concentration of loads as opposed to the natural wandering in manual driving. This platooning phenomenon will cause an increase and acceleration of damage [37] [38]. Gungor and Al-Qadi [39] have proposed the strategy of having the passage of successive platooning positioned transversely in a variable way, in order to distribute the loads. Moreover, this distribution of loads can be optimized to reduce stresses, even with respect to the usual normal distribution in human driving. Therefore, at least the right lane on a freeway should not be narrowed to adopt load wandering strategies for successive platooning.

Finally, the median type refers to the road infrastructure that separates opposing traffic flows. Despite the great importance of road marking line width and condition on CAV readability, the proximity of the line to materials such as concrete shoulder and concrete safety barriers also plays a critical role in CAV performance as they have similar properties to lines from a machine learning perspective [40]. Additionally, the installation of small objects in the median –e.g., cable median barriers– may make difficult object detection [41].

3.2.4. Road markings

Lane detection and tracking, as well as identification and recognition of road markings on the pavement, play an important role in driver assistance systems, vehicle guidance, and route planning [42]. Thus, many studies have been carried out to develop algorithms that allow real-time detection of lane edges and enable vehicle guidance [43]. However, the number of studies developed in the field of detecting horizontal pavement markings is lower [44].

Additionally, most of the research has focused on studying the phenomenon from the hardware and software perspective, i.e., image recording device and detection algorithms. However, an essential role in this phenomenon is also played by the infrastructure factor [45]. Therefore, this section focuses on the analysis of road marking detection from the infrastructure factor perspective so as to characterize the phenomenon and identify the limitations of the systems incorporated in current Connected and Automated Vehicles.

Most CAVs have a high accuracy level while detecting pavement markings under the following conditions considered as ideal [46] [47]:

- Roadway with proper visibility.
- During the middle hours of the day, when the incidence of sunlight on the vehicle hardly produces shadows.
- Ideal weather conditions, no clouds and dry pavement.
- Ideal pavement surface conditions with no deterioration or obsolete road markings that could be misinterpreted by the machine vision system.
- Continuous and uninterrupted road markings in accordance with existing standards.

In any other case, the accuracy level associated with road marking detection significantly decreases, being the worst conditions:

- Frontal incidence of the sun.
- Nighttime conditions: poorly lit or unlit roads.
- Cloudy conditions or rain that darken vision.
- Wet roads or snow-covered roads.
- Pavement in poor condition or obsolete road markings.
- Deteriorated road markings or not complying with standards.
- Combinations of the above.

One of the first studies on CAVs performance related to the influence of road marking quality, light conditions –day vs. night–, and pavement condition –dry vs. wet– on road marking detection was developed by Davies [48]. As a result, the higher the level of retroreflectivity of the road marking, the higher the probability of detection, up to a value of 400 mcd/m2/lx. Moreover, a retroreflectivity of 150 mcd/m2/lx has been stablished as the minimum level required to ensure a proper CAV operation [49] [50]. Davies [47] also concluded that white road markings were easier to detect than yellow ones, while a wet pavement led to a drastic drop in system performance. Finally, road markings with a width of 6 inches (150 mm), in addition to performing better than 4 inches (100 mm) in terms of detection, in some cases helped to counteract the low retroreflectivity by facilitating the task of vehicle positioning.

Pike et al. [45] focused on the analysis of the road marking width under different light and weather conditions. Specifically, in this research, the two common widths used on US roads, 4 inches (100 mm) and 6 inches (150 mm), were analyzed. The results of the research showed that 150 mm longitudinal markings provide a greater accuracy in line detection in most, but not all, of the scenarios evaluated compared to 100 mm line width. Nevertheless, CAVs performance was also high in dry daytime and nighttime conditions with 100 mm road markings in good condition (markings with retroreflectivity, color, and contrast levels that would generally be considered adequate by current practices or standards). In fact, in these cases, increasing the width of the road markings to 150 mm did not have a significant impact. Increasing the width from 100 to 150 mm did indicate a significant improvement in road marking detection when detection did not provide good results in the 100 mm case. Specifically, it was observed that the greatest detection problems occurred under wet daytime conditions. In this context, 150 mm markings significantly improved CAVs performance. In addition, it was observed that the system performance in wet conditions was better during nighttime than daytime conditions.

Despite the great contributions of this research, one of the most important limitations of this research was that the entire study was carried out on a test track, with the road markings in good condition. However, the longitudinal markings wear out and the edges of the markings are no longer linear, which makes detection by the system difficult. It is therefore recommended to use a road marking width of 150 mm instead of 100 mm, as the reliability over time will be higher.

As a result of the NCHRP 20-102(06) project, it was determined that the contrast ratio of longitudinal pavement markings in relation to the pavement should be approximately three. In other words, the luminance factor or retroreflected luminance (R_L) coefficient should be three times greater at the pavement markings than at the pavement surface [47].

More recently, Austroads [51] analyzed in more detail the performance of the cameras equipped in Automated Vehicles with respect to road marking detection. A total of seven Automated Vehicles driving in four scenarios on test tracks and three sections of existing roads were considered travelling at 60 and 80 km/h. All vehicles, of different car brands, were equipped with the Lane Keeping Assist (LKA) system. Table 12 summarizes the most important findings of this research which can be grouped into six main factors: (i) contrast, (ii) geometric design, (iii) design and maintenance guidelines, (iv) environmental conditions, (v) pavement type, and (vi) operation.

Factor	Findings
Contrast	- Current road marking detection systems require a minimum 3:1 contrast ratio (Qd) between the road marking and the pavement. - In nighttime conditions, current systems can detect road markings when the contrast ratio between the road marking and the pavement, measured from retroreflectivity (R_L), is between 5:1 and 10:1. - Pavement glare that occurs under certain situations can reduce the capability of current longitudinal marking detection systems as it reduces the contrast between road marking and pavement.
Geometry	- Current systems can detect the current widths of 150 mm for edge lines and 100 mm for dashed lines. However, road markings tend to degrade over time, so it is recommended to increase the width of dashed lines to avoid malfunctioning of the systems during the life cycle of the road marking. - Discontinuous road markings present greater detection difficulties than continuous ones. - To provide continuity to road markings on both sides of the lane, avoiding extended gaps and ensuring fixed lane widths, eases lane markings detection mainly on exit ramps and intersections [10]. - Lane widths that are too wide or too narrow make the task of detecting longitudinal pavement markings more difficult. It is suggested to use widths between 2.6 and 4.2 m.
Design and maintenance	- Most of the recent harmonization standards for road marking design meet or exceed the requirements for machine vision systems. - Although there are uncontrollable factors that can hinder the capability of detection systems, improved maintenance and design principles for road markings can provide very significant benefits to the detection task. - Usually, management has very little information about the level of deterioration of road marking and signaling systems, resulting in poor maintenance processes.
Environmental conditions	- The variability of light conditions during the day makes lane detection less effective than at night.

Factor	Findings
	- When the pavement is wet, the functionality of detection systems can vary greatly. While a minimal ambient light may increase contrast and therefore enhance detection, under excessive ambient light a "light bloom" effect may occur, significantly reducing the capability of the detection system. - In rainy periods the functionality of the detection systems decreases significantly.
Pavement type	- While the Mobileye system performed similarly during detection on asphalt and concrete pavements, the vehicles used in the tests had better detection rates on asphalt pavements.
Operation	- The speed at which vehicles operate is a key factor for detection systems. In this regard, some vehicles improve their performance at higher speeds and others reduce their functionality.

Table 12. Road marking influence on CAVs performance [51].

The Society of Automotive Engineers (SAE) has recently published a study that presents a benchmark test that allows establishing the functionality of Automated Vehicles based on the evaluation of the condition of road markings and pavement type [52]. For the development of this research, the performance of edge road marking detection algorithms incorporated in current Automated Vehicles was assessed during different hours throughout the day (11 a.m., 6 p.m., and 10 p.m.). As a result, Nayak et al. [52] identified that road marking detection systems operate best during the central hours of the day, i.e., when there is hardly any shadow, no glare, and relatively constant pavement luminance. On the contrary, the greatest detection problems were recorded during the evening (6 p.m.), which were attributed to the direct incidence of the sunbeams on the camera and the high reflection of the sun on the pavement. This phenomenon produces a reduction of the contrast between the pavement and the road marking, which negatively affects the identification of lane edges. However, during the same hours and driving in the opposite direction to the direct incidence of the sun, a high rate of identification of the road markings was observed thanks to the improvement of the lighting conditions for the camera. Finally, it was concluded that nighttime conditions increase the contrast between the pavement and the road markings, which improve the identification of road markings. Related to this, the higher the retroreflectivity (R_L), the better results were observed in the identification of road markings.

3.2.5. Traffic signs

Traffic signs from Vienna Convention and MUTCD are, in general, easily detectable by Traffic Sign Recognition (TSR) systems, since TSR systems are trained and adapted to these traffic signs. In addition, these systems are initially based on the recognition of the shape of the signal, moving on to the recognition of the colors, and finally the text or pictogram. For this reason, the Vienna Convention, which is more symbol-based, makes TSR performance particularly easy.

It is recommended to unify, at least at the European level, aspects such as fonts, pictograms, and arrows. This would lead to an easier recognition by the systems, facilitating recognition in real time.

Regarding color, TSR systems can easily recognize blues and greens as opposed to reds. The latter can sometimes be confused with oranges or yellows, especially when ambient light conditions may require a significant variation in white balance. This implies that the yellow background of certain signs can sometimes be mistaken for a white background.

Current TSR systems recognize only a few types of traffic signs, being the most important ones the following [53]:

- Posted Speed Limits are the most widely recognized traffic signs.
- Priority of way such as STOP, yield, and the like. These signs are much less well recognized by the systems because TSR systems are not all yet trained to recognize these types of signs.

The fact that TSR systems are primarily geared to recognize speed limit signs makes logical sense as these traffic signs are the baseline information that is often used by the vehicle for the adaptive speed system (ISA). In contrast, other signs do not provide such easily interpretable information for vehicles or are not linked to a specific Advanced Driver Assistance System (ADAS) on the market today.

However, TSR systems do not recognize advisory speed signs. It is important to differentiate between the system not recognizing these signs and the system recognizing that there is a sign but not interpreting it correctly. In the latter case, for instance, a 60 km/h end of restriction sign could be mistaken for a 60 km/h restriction, when the regulation is completely the contrary. In the first case, the system would not interpret anything. A research in Australia concluded that TSR systems disregard advisory speed signs, avoiding the confusion of the system [53].

Currently, a very important technological limitation does exist in terms of the contextual information that regulates when a certain sign applies –in general, hourly, daily, meteorological or by vehicle type–. This is usually done by means of complementary panels located under the sign. As they are outside the frame of the sign, the systems usually interpret only the sign, ignoring the complementary information. Thus, an 80 km/h limit sign in heavy rain is interpreted by the automated driving system as an 80 km/h restriction at all times. This is much more serious in countries like Australia, where the end of restriction is indicated with the limitation sign and a complementary "END" panel, which would not be interpreted. Manufacturers and suppliers are working on solving these concerns [53]. Although most of the systems cannot recognize the text, they do display warning messages (such as "!") on the dashboard when complementary panels are provided. To make these panels easier to read in the near future, it is recommended the texts be large and clear [53]. Additionally, there are other non-standardized signs, especially at local level, for which the system obviously cannot be trained and therefore is not able to recognize.

The size, position, and placement regulations related to traffic signs pursue two main objectives:

- The sign must be clearly visible at a sufficient distance, by the vehicles to which it will apply.
- The scope to which vehicles the traffic sign applies must be clear.

In order that traffic signs are recognized early enough, they must be positioned in such a way that:

- They come within the angle of vision of the camera.
- There are no obstacles between the vehicle and the sign.
- There is no excessive angle between the road and the sign orientation.

Currently, there are few studies aimed at determining the performance of TSR systems against these variables. One very comprehensive study was conducted by Austroads in 2018, in which the performance of five vehicles of different car makers was assessed in four environments: a test track, and three real environments in Melbourne, Sydney, and Auckland. While not all vehicles were tested in all environments, the observed variability allowed drawing some general conclusions on the performance of a wide variety of TSR systems. In particular, it was found that TSR systems performed better in real-world environments than in test tracks due to the combination of visual information and online maps made by the systems [53]. Table 13 shows the TSR system performance concerning variations in position and orientation of the traffic signs.

Factor	Findings
Side	- Signs are correctly displayed regardless the roadside in which are located. - The background of the Region Of Interest (ROI) on which the image is placed does not seem to affect recognition.
Horizontal curve	- A slight variability in sign detection was identified when the signs are located at curves.
Transverse distance	- Moderate distances do not seem to have an impact on recognition (background of trees was tested, which contrasts with the sign). - Up to distances of 10 m, there is significant variability in sign recognition: some vehicles are able to recognize it and others are not.
Orientation	- Up to 45° with respect to the perpendicular to the road, the sign is recognized in most of cases. - Between 45° and 55°, the recognition shows considerably more variability between systems.
Multiple signs	- In juxtaposed signs with different speed limits, a great variability of responses is observed. In most cases, the most restrictive speed limit or the one closest to the road is detected. - In signs placed simulating an exit ramp, a large variability is also observed. In some cases, the system did not indicate any speed. In some others, the speed of the main section is detected.

Table 13. Influence of sign position and orientation on TSR system performance [53].

In many cases, sign position also influences the visibility of the sign (e.g., it may be hidden by another sign, a street light pole, or vegetation). To this regard, Lengyel and Szalay [54] proposed a set of criteria to be able to determine the response of TSR systems to variations in sign visibility, lightness, recognition, position, and simplicity. In addition to proposing the criteria, the performance of the TSR system of a vehicle was analyzed at different speeds –10, 30, and 50 km/h–. The results of the study are shown in Table 14.

Criterion	Description	Findings
Visibility	Ability to recognize the sign partially hidden by vegetation or a pole.	- The system can read the sign as long as it is not excessively obscured. It is slightly more reliable if the obstruction visibility is by a pole than by vegetation.
Lightness	Ability to recognize the sign under different lighting conditions.	- Results highly conditioned to the orientation of the sign in relation to the light source.
Recognition	Ability to recognize the sign partially hidden by stickers or by deforming its shape (simulating graffiti or vandalism).	- Except for the worst cases of overlap, the system was able to recognize the sign. - The recognition mainly depends on the part of the sign that is masked. If it affects the number, the recognition capability decreases greatly. - In the case of deformation, the system seems to be able to detect the sign at any speed, although it did not become excessively deformed.
Position	Ability of the system to recognize signs at different heights.	- No problems were observed in detecting the sign at different heights, although the heights did not vary too much.
Simplicity	Ability of the system to detect the most restrictive sign, between two juxtaposed signs.	- The system showed, at all speeds, the highest post speed limit sign.

Table 14. Criteria and findings of the research developed by Lengyel and Szalay [54].

The maintenance of the traffic signs is also very important for their readability by TSR systems. Maintenance covers many aspects, including that the sign is not dirty or vandalized, not deteriorated, and logical in its environment (i.e., remove those signs that no longer need to be applied).

The visualization of the image from TSR systems is greatly complicated in situations of low or altered lightness (e.g., at night, at dusk, with glare or under adverse weather conditions). At night, the absence of light leads to low contrast and color saturation. Moreover, different light sources (e.g., headlamps of other vehicles or streetlights) produce changes in color tone. Adverse weather conditions, such as rain, snow or fog, cause blurring of the image and possible glare. This also reduces the contrast of the image, making it more difficult to identify. This difficulty varies depending on the intensity of these phenomena.

These conditions are so different from the standard ones that, sometimes, completely different methods are needed for sign recognition [55]. Some research has focused on improving TSR algorithms to be able to distinguish signs under these conditions. Thus, Temel et al. [56] worked on expanding the sign databases with variations including different levels of darkness, rain, fog, lens dirt, and so on. Suzuki et al. [57] worked not on the databases, but on improving edge detection of forbidden direction signs at night conditions. Mannan et al. [58] developed a complex system based on convolutional neural networks, starting from the altered GTSDB (German Traffic Sign Detection Benchmark) with adverse visualization conditions.

Another option to ensure proper visibility of these signs lies in setting a minimum level of retroreflectance on the signs. Currently, no in-depth studies have been carried out analyzing what is the minimum level of this variable that would guarantee correct detection and recognition by TSR systems. In the report prepared by Austroads, road owners were asked for this issue and recommended either to follow the existing regulations or to ensure visibility at a minimum of 150m [51].

Furthermore, Variable Message Signs (VMS) are not always read consistently by TSR systems [53]. The inclusion of text in the VMS increases exponentially the difficulty of message adaptation by vehicles due to both semantic aspects and heterogeneity of messages – including the language –. In addition to the above-mentioned limitations for static signs, VMS present following additional limitations linked to the intrinsic aspects to this technology:

- Contrast and adaptability to surrounding light.
- Interpretation of LEDs to form characters and pictogram.
- Maintenance.
- Image flickering.

However, new technologies are being developed to address these limitations –e.g., CMOS sensors that include LED Flicker Mitigation (LFM)– [51].

3.2.6. Junctions

All studies discussing the benefits of CAVs at signalized intersections pointed out an important reduction in the number and severity of traffic conflicts and crashes [59] [60] [61]. For penetration market rates (PMR) between 50% and 100%, CAVs reduce the number of traffic conflicts by 20% to 65%, respectively [61]. In the case of roundabouts, the reduction is expected to be by 29% to 64% with a full automated traffic (i.e., 100% PMR) [61]. Likewise, connected vehicle technology could significantly improve the operation of traffic at signalized intersections [62]. Increases in the PMR from 0% up to 60% can significantly reduce the average delay. For instance, a decrease in delay of up to 60% was identified in low demand scenarios. However, the achievement of these figures is only possible with high levels of automation, i.e., these vehicles must provide a high level of connectivity. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications play an important role to this regard [60].

The expected connected mobility also requires a reassessment of traffic management. To raise the level of safety at signalized intersections, an increase of the duration of the yellow phase might be needed to allow CAVs the development of all required collision avoidance maneuvers [63]. Obviously, this fact leads to a reduction of the intersection capacity and, consequently, a possible traffic jam. Special attention should be paid to traffic lights. The general problem of identifying traffic lights and their states is known as Traffic Light Recognition (TLR). Despite the large number of studies focused on this issue, there are still some important weaknesses to be addressed [64]. Currently, CAVs have difficulties to recognize traffic lights under special light conditions such as receiving the sunlight from behind the vehicle, which produce that all lamps appeared to be lit, or at nighttime, where yellow and red lighting colors could be visually recognized to the same color when processing the image [65].

A critical situation when travelling through traffic lights is predicting green traffic lights while facing red ones. To deal with this type of error, some studies have been developed to increase the recognition accuracy by merging the information provided by TLR systems and HD maps [66] and connecting traffic regulation through C-ITS [67]. In the long run, traffic lights might be removed to the detriment of the appearance of slot-based intersections [68]. This idea relies on a scenario where sensor-equipped vehicles travel through intersections by communicating and remaining at a safe distance from each other, rather than stopping at traffic lights. An important advantage of this approach is its flexibility and compatibility with the accommodation of pedestrian and bicycle crossings.

Regarding interchanges, entrance ramp maneuver has been also studied [69] [70]. First, Wei et al. [69] highlighted the importance to consider common drivers' behavior to formulate more accurate algorithms to safely enter in high-capacity roads. Moreover, Algomaiah and Li [70] introduced a Next-generation Interchange Control (NIC) algorithm to deal with service interchange terminals for CAV with the ability to adjust the dimensions and geometric designs. After analyzing six different geometric designs, tight turn with one left dedicated turn provided the highest performance, while wide turn with two left shared turns resulted in the lowest performance. Both NIC designs demonstrated significantly higher throughputs and significantly lower delays compared to a current traffic signal system.

Moreover, Wang et al. [71] analyzed the Operational Design Domain of Automated Vehicles, defined as the required detecting angle and distance within the skewed intersection's speed range. As a result, intersection angle was found to have greater influence on the detecting angle when the road design speed was higher than 40 km/h, and the obtuse-side detecting distance increased rapidly when speed on the major road reached 50 km/h.

3.2.7. Pavement condition

Although a few studies have been developed to quantify the influence of pavement condition on CAVs performance, it is clear that the state of the pavement surface plays a critical role in automated driving [42]. To this regard, the new road classifications that include the particularities of this type of vehicles stablish that a good pavement condition is needed to achieve the highest levels of automation (see 3.1.2. Road Classifications for Connected and Automated Vehicles).

Particularly, asphalt pavements provide a better CAVs performance than concrete pavement as the first ones ease the contrast between road markings and pavement [51]. Additionally, sudden road distresses (e.g., potholes or rutting) and old road markings might cause unexpected system disengagements. Poorly removed pavement markings that diverge from pavement marking across the wheel path will often confuse the machine vision, causing dangerous vehicle maneuvers. Related to this, the reflection caused by the sun on crack sealing might also be interpreted as road markings by CAVs, leading to a non-desired performance.

Road pavement roughness can create some discontinuity when the camera captures the line marking and this may negatively impact on machine-vision performance. However, time and cost limitations made it difficult to assess and anecdotal comments were instead recorded on this point [51]. As shown in Figure 6, the machine vision camera's ideal focal length is partially blocked by patches of uneven surface –green areas can be seen but red areas cannot–.

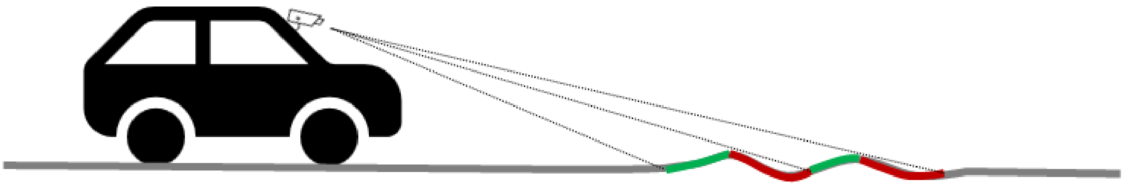


Figure 6. Influence of road pavement roughness on CAV performance.

In addition, when an automated vehicle is following or close to another vehicle, a sudden and abrupt change of the trajectory of the preceding vehicle as a result of significant pavement damages might lead to an unmanageable situation for the automated vehicle.

Another important issue regarding pavement is that the particular operation of CAVs –travelling continuously in the middle of the lane– will accelerate the appearance of rutting and other pavement deteriorations (e.g., potholes and cracking) [22]. Therefore, in CAV-dedicated lanes, higher stiffness and more resistant materials should be considered for the surface layer. The maintenance frequency for the remaining pavement layers can also be increased in the future. To address this concern, recent studies proposing lateral control modes for automated vehicles have been developed [72].

3.2.8. Road environment

In addition to the geometric design, pavement, and road signage, there are other factors related to the infrastructure, such as street lighting, bridges, and tunnels, that can influence the performance of CAVs.

Previous studies concluded that the installation of new lighting where no lighting was present can reduce night-time crashes by 30-50% [73]. Specifically, crashes in poor lighting conditions –even with lighting on– led to a much greater number of casualties than those in daylight, for both automated and conventional driving modes [74]. In fact, higher odds of injuries are expected in automated driving. In this context, an improvement of street lighting, in terms of better illumination or more closely spaced lights, may be required to ensure that the visibility of road markings, signals, and signs is suitable for an effective CAVs performance [75].

Furthermore, tunnels present two important issues: (i) sudden changes in illumination conditions and (ii) low GNNS signal coverage. When an automated vehicle –commonly perceiving environment through vision cameras– enters or exits a tunnel, the sudden changes in environmental lighting might lead to a reduction in object recognition accuracy. To enhance road marking detection and traffic sign recognition at these critical points, diverse studies have proposed the early detection of the tunnel to apply specific algorithms [76] [77].

Current automated vehicles combine the information retrieved from the global positioning system (GPS) and the inertial navigation and vision systems for the positioning task. To this regard, an important limitation arises when positioning the vehicle in shaded areas of GPS, like tunnels. To address such limitation, some studies have presented some innovative solutions:

- Use of LED lighting [78].
- GPS, Lidar, and derivative data fusion [79].
- Landmark-based local positioning system [80].
- C-V2X positioning systems [81].

However, further research in this field is required to stablish standardized solutions and consistent with automated vehicles' capabilities.

3.2.9. Environmental conditions

The main environmental factors affecting CAVs performance are weather and lighting. Unfavorable weather conditions –heavy rain and fog– makes road marking and traffic sign recognition very difficult as these tasks are carried out by vision cameras that are very sensitive to visibility [51]. In rainy periods, the functionality of the detection systems decreases significantly.

Furthermore, the performance of detection systems can vary greatly when the pavement is wet. While a minimal ambient light may increase contrast and therefore enhance detection, under excessive ambient light a "light bloom" effect may occur, significantly reducing the capability of the detection system [51].

The variability of light conditions during the day makes lane detection less effective than at night. However, street lightning at night reduces the accuracy of vision cameras concerning color distinction [65]. As mentioned previously, the vision systems installed in CAVs might confuse yellow and red lighting colors leading to a misinterpretation of traffic lights. According to Shladover and Bishop [82], ensuring that the visibility of road markings, signals, and signs is suitable for CAVs to perform effectively may require improved street lighting, either through better illumination or more closely spaced lights.

Automated Vehicles are also susceptible to glare caused by direct sunlight. Cameras capturing images of direct sunlight with standard dynamic range must correct for the bright sun and the resulting image typically has an over-exposed background and an under-exposed foreground. This phenomenon caused, in 2016, the first death in an autonmated car occurred when a Tesla Model S collided with a white tractor trailer [83]. Since then, some research have been developed to enhance object detection in direct sunlight [84].

3.2.10. Vulnerable road users

Some studies were focused on identifying the potential for CAVs in reducing pedestrian fatalities [85] [86] [87] [88]. To this regard, the decision algorithms responsible for pedestrian crossing identification are continuously updated so as to gather as many pedestrian behaviors as possible. However, the trajectory of a human is sometimes unpredictable, rising the likelihood of crash occurrence. Combs et al. [85] concluded that sensors' abilities to detect pedestrians in advance of fatal collisions vary from 30% to 90% of fatalities. Combining sensor technologies provides the highest potential for removing fatalities but may be unrealistically expensive. Real-time object recognition studies have so far released satisfactory results for pedestrians using pedestrian crossings, but further research is needed focusing on sensing and detection capabilities for pedestrian crossing facilities [89].

According to Fairley et al. [90], the main challenge for CAVs is posed by the lightest, quietest, most swerving vehicles on the road, i.e., bicycles. Current technology has difficulties in predicting cyclist behavior. In addition, the identification of this type of vehicle can confuse the system as two objects –bicycle and human– are separately detected.

Many car manufacturers, supported by scientific research, are developing safety and communication systems that aim to avoid collisions with non-motorized vehicles, such as pedestrians and cyclists. However, most of these developments are being performed especially from the perspective of the vehicle, neglecting the phenomenon from the perspective of the pedestrian and the cyclist [91]. Many difficulties are yet to be overcome (e.g., reliable operation in adverse weather conditions), and it is even more challenging to develop technology that can reliably predict intentions and behavior of pedestrians and cyclists.

Current interaction patterns and strategies cannot be automatically transferred to a situation with automated vehicles or to a situation with vehicles with different levels of automation [91]. Pedestrians and cyclists might base their behavior on incorrect or unjustified expectations about the behavior of these vehicles. Similarly, the vehicles might not be able to interpret the behavior of pedestrians and cyclists correctly, because their behavior in interaction with an automated vehicle could differ from the behavior towards a human-driven vehicle.

Another group of vulnerable users are powered two-wheelers, which are hardly detected by CAV sensors and algorithms [92] [93]. A study focused on the analysis of the capabilities of the Adaptive Cruise Control integrated in different car models of various car manufacturers –Jeep, Hyundai, Skoda, Volvo, VW, and Tesla– concluded that motorcycles detection is only possible when the motorcyclist is riding more than 1.20 m from the centerline of the vehicle/lane [92] (Figure 7).

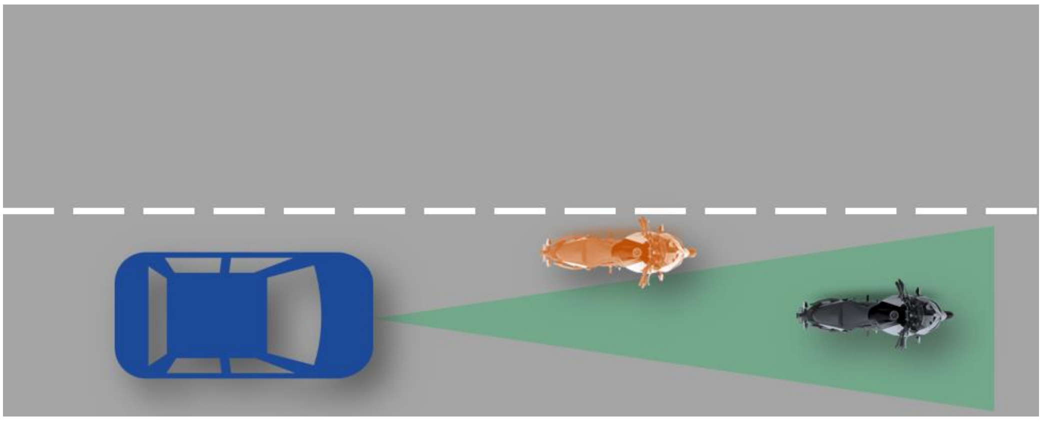


Figure 7. Adaptive Cruise Control limitations.

3.2.11. Road works

Traffic Sign Recognition systems are not well suited to road works signaling [53]. The limitations do not lie in recognizing the sign itself or the road marking (despite their differences in color), but in differences in placement (signs are often placed on the roadway itself, sometimes without following strict indications of distance from the work site or lane orientation, and even at very low heights). Coexistence with usual signage should also be studied when these are contradictory. Regarding road markings, the coexistence of longitudinal temporary and definitive road markings might be problematic for vehicles as well as the presence of cones on the roadway. Moreover, erased or covered road markings might be an issue.

3.2.12. Temporary emergency signage

Temporary structures might be placed on the road due to local requirements or crashes, including temporary emergency signage that may obstruct or impact normal driving. The algorithms of CAVs are not ready to identify and interpret signage that, in many cases, does not comply with any regulation or guideline. For instance, current CAVs can identify pedestrians, but not interpret police officers' signals. In short, temporary emergency signage does not follow clear and defined patterns which makes its interpretation even more difficult than road work signage.

A quick geo-reference of this type of signage in HD maps would ease its recognition and allow CAVs to manage the information in advance.

3.2.13. Speed

Advanced Driver Assistance Systems (ADAS) are usually limited to specific range of speeds. While Adaptive Cruise Control (ACC) usually works from 30 km/h, Lane Keeping and Centering Assist (LKA and LCA) systems work when the vehicle speed is over 60 km/h. Therefore, most of current automated vehicles cannot operate in an automated way in urban environments –50 km/h maximum speed limit– due to factory constraints.

Different types of Intelligent Speed Assistance (ISA) systems have been developed, providing different levels of support and feedback to drivers [94]:

- Advisory/Warning (open).
- Supportive/Intervening (half-open).
- Mandatory limiting/Automatic control (closed).

While an open level of support only warns the driver in case of exceeding the posted speed limit at a specific location, the half-open level is able to control throttle, but the driver can still exceed the speed limit. By contrast, a closed system does not allow drivers to exceed the speed limit as the maximum speed of the vehicle is automatically limited. In this context, ISA systems can use speed limits in diverse ways:

- Static speed limits, i.e., posted speed limits.
- Variable speed limits, i.e., lower speed limits at specific locations such as sharp curves or work zones.
- Dynamic speed limits, i.e., speed limits based on the actual road and traffic conditions.

Nevertheless, for high level of automation, the ISA will need to be based not only on the speed limits, but also on the operation speed profiles chosen by the automated system or set by the Traffic Management Center. This new ISA level could be named dynamic-closed.

Moreover, speed is a critical factor in road marking recognition because the system needs to process the gathered information faster as the vehicle speed increases. Related to this phenomenon, García et al. [7] defined the Automated Speed as the maximum speed that an automated vehicle can achieved at a specific road geometric element. In this way, demanding road elements such as sharp horizontal and vertical curves are associated with lower automated speeds. Thus, high-capacity rural roads (e.g., freeways and expressways), which are usually characterized by a smooth road geometric design, allow CAVs to operate in an automated way. However, two-lane rural roads, that commonly consist of numerous demanding road elements, could produce continuous system disengagements [7,8].

Regarding road marking configuration, dashed line recognition also depends on vehicle speed. A research conducted by Austroads [51] concluded that a 150 mm width, 9 m solid, and 3 m space road marking was detected in a more accurate way at 60-70 km/h than at 80 km/h. In contrast, a 150 mm width, 3 m solid, and 9 m space road marking resulted in a 100% and 90% of accuracy detection at 80 km/h and 60-70 m/h, respectively.

Along roads with a fair or poor pavement condition, speed also plays an important role. Pavement distresses will cause more critical vehicle movements at higher speeds leading to more frequent system disengagements.

3.3. Connectivity limitations

Vehicle to Everything (V2X) is a communication system which interconnects a road vehicle to any entity that may concern it. A broad concept, V2X encompasses a range of communications channels, including:

- Vehicle to Vehicle (V2V): Direct communication between two vehicles.
- Vehicle to Infrastructure (V2I): Communication between a vehicle and fixed infrastructure, such as traffic lights, infrastructure monitoring and control devices, parking services, etc.
- Vehicle to Pedestrians (V2P): Communications between vehicles and pedestrian devices, alerting pedestrians of vehicle movements and warnings for vehicles.
- Vehicle to Device (V2D): Communication between vehicles and non-V2V enabled vehicles and cyclists.
- Vehicle to Network (V2N): Communications with the cellular network, either to facilitate other types of V2X communications, or to access internet resources.

Currently, there are two V2X communication approaches using different underlying technologies that have been defined by the IEEE (Institute of Electrical and Electronics Engineers) and the 3GPP (3rd Generation Partnership Project), respectively. The IEEE's approach is DSRC (Dedicated Short-Range Communications), which supports vehicular ad-hoc connectivity WLAN technologies standardized as IEEE 802.11p [95]. This technology is known in America as Wireless Access in Vehicular Environments (WAVE) and in Europe as ITS-G5, being the basis for the European standard ETSI ITS-G5. The second approach is based on cellular technologies and known C-V2X (Cellular V2X –Vehicle-to-Everything–) [96] and proposed by the 3GPP. C-V2X is based on LTE (Long Term Evolution) or more recently on 5G NR, also known as LTE/NR-V2X (Direct communication specified by 3GPP R16 based on a new radio (NR) interface).

Previous ETSI ITS (European Telecommunication Standards Institute) –current European vehicular communication technology standard– and the American IEEE 1609 family of standards, also known as Wireless Access in Vehicular Environments (WAVE), may operate with either IEEE 802.11p/ITS-G5 or C-V2X as access technologies. In fact, to make the deployment of both European approaches possible, these access layers were standardized in 2020 as European Standards/Norms that specify the operative details for their use in the 5.9 GHz ITS band in Europe [97]. Similarly, in the US, the IEEE 1609 and the application layer message standards of the Society of Automotive Engineers (SAE) International allow both access layers, with SAE International even defining profiles and testing standards for each access layer. Adding to this is the layered definition of the IEEE 1609 standards, which allows WAVE the use of C-V2X and not only of the 802.11p based access layer; and also makes it possible that LTE-V2X could use WAVE security standards such as IEEE 1609.2. In fact, the WAVE Network Services standard (IEEE 1609.3) has been updated to operate with DSRC or LTE-V2X, equally.

In June 2020, the Rel-16 based 5G V2X standard was officially completed [98] including C-V2X communications based on 5G New Radio (NR) as a complementary access technology in order to provide sophisticated applications and use cases with more stringent Quality of Service (QoS) requirements (e.g., platooning, advanced driving, etc.) [99]. Rel-16 based 5G V2X is also backwards compatible with LTE-V2X. There are no NR-V2X (Vehicle-to-Everything standard based on the 5G New Radio (NR) air interface) devices in the market yet although some prototypes are already available. Additionally, the simultaneous use of both 4G and 5G-enabled radio modules for V2V communications is possible as a result of network-controlled coexistence enhancements introduced recently by C-V2X [100].

Both WAVE and C-V2X support direct communications between vehicles (V2V) as well as communication with infrastructure (V2I). Services based only on V2V communications only require the availability of the radio module in each vehicle, i.e., the transmitter, and a spectrum allocated to the service. However, in order to support V2I applications, WAVE would require deploying a specific network along supported roadways. C-V2X technologies, either 4G or 5G, could make use of pre-existing cellular networks already deployed by any operator.

Independently on the specific technology, services enabled by V2X can be classified into different levels of connectivity, as specified by the ISAD classification, depending on the consideration of the exchange of status data to enhance predictive driving, the exchange of sensor data, or the exchange of intention data which provides a better coordination of vehicles to allow automated driving.

DSRC is a communication method with a limited range (tens of meters) and the vehicle speed has to be relatively low for switching and communicating with any Roadside Unit (RSU). Another issue is related to overcrowding under high traffic volume [101].

The performance of the two main V2X technologies degrades as the number of connected devices increases. Moreover, the deployment of the next-generation cellular network infrastructure should increase the capacity and throughput and decrease the latency. Other key factors will be the signal strength and possible interferences.

The typologies of communication should most likely still be:

- Vehicle to Vehicle short range.
- Vehicle to Infrastructure short range.
- Vehicle to Infrastructure medium/long range.

The last one will probably be provided via cellular networks, but the short range V2I communications will need RSUs beside or over the road, connected to different servers (road operators, vehicle manufacturers, service providers, fleet managers, etc.) by means of trunk communications, such as fiber optic cabling [102].

Additionally, high requirements for large-bandwidth low-latency communications should be satisfied due to the overlapping of safety communications (e.g., work zones and traffic crashes) while keeping the lower priority demands. When automation reduces the requirements towards driver attention, the use of infotainment services and mobility planning platforms will become more frequent, which can lead to safety issues [102]. The cooperation between communication and autonomous mobility will only be possible with a joint effort from the public and private sector to connect vehicles, roads, and customers. The "5G Strategic Deployment Agenda for Connected and Automated Mobility in Europe" [103] noted that identifying appropriate cooperation models is critical in fast-tracking the much-needed 5G V2X infrastructure deployment. From the non-mutually exclusive options identified by the European Commission for cooperation models applicable to 5G Connected and Automated Mobility (CAM) infrastructure deployment, a recent 5GAA Whitepaper [104] highlights the strategic value of four of them: (i) enabling wholesale open access models, supported by the investment in passive infrastructure by a single Neutral Host Provider (NHP), (ii) investment in passive infrastructure by a road or rail operator, (iii) co-investment in active cellular infrastructure and RSUs by a joint venture of interested companies –NHP, Mobile Network Operator (MNO), road/rail operators–, and (iv) investment in active cellular infrastructure by MNOs along the roads.

As a summary, a highly versatile framework that supports several wireless technologies is needed, especially to allow high-level automation. For that purpose, a strong cooperation between all stakeholders is mandatory.

Since 2015, Huawei quantifies the level of connectivity per country based on the Global Connectivity Index (GCI) [105]. This index considers a total of 40 variables grouped into four main pillars (Figure 8):

- Supply.
- Demand.
- Experience.
- Potential.

For each variable, a country is ranked from 1 (low) to 10 (high), depending on the data input. Each indicator has a scale based on a realistic target value for 2025. Scoring more than "10" indicates that the target value has been reached.

Figure 9 shows the relationship between GCI 2020, being its maximum value 120, and Gross Domestic Product (GDP) per capita. GCI 2020 showcases the influence of 5G and Artificial Intelligence on GDP growth, which is particularly important for policy makers as they strive to help lead their economies from the COVID-19 pandemic towards a more competitive position through the digitalization of their economies.

Four Pillars

Four Technology Enablers	SUPPLY	DEMAND	EXPERIENCE	POTENTIAL
	Measures current levels of supply for ICT products and services used for digital transformation.	Gauges demand for connectivity in the context of users and activities relating to digital transformation initiatives.	Comprises variables for analyzing the experience of connectivity for end users and organizations in today's digital economy.	Comprises a forward looking set of indicators that point towards the future development of the digital economy.
FOUNDATION	ICT Investment Telecom Investment ICT Laws International Internet Bandwidth Security Software Investment	App Downloads Smartphone Penetration e-commerce Transactions Computer Households Secure Internet Servers	E-Government Services Telecom Customer Services Internet Participation Broadband Download Speed Cybersecurity Awareness	R&D Expenditure ICT Patents IT Workforce Software Developers ICT Influencing New Business Models
BROADBAND	Fiber Optic 4G&5G Connections	Fixed Broadband Subscriptions Mobile Broadband Subscriptions	Fixed Broadband Affordability Mobile Broadband Affordability	Broadband Potential Mobile Potential
CLOUD	Cloud Investment	Cloud Migration	Cloud Experience	Cloud Potential
INTERNET OF THINGS	IoT Investment	IoT Installed Base	IoT Analytics	IoT Potential
ARTIFICIAL INTELLIGENCE	AI Investment	AI Demand	Data Creation	AI Potential

Figure 8. Pillars and variables considered by the Global Connectivity Index. Source: Huawei [105].

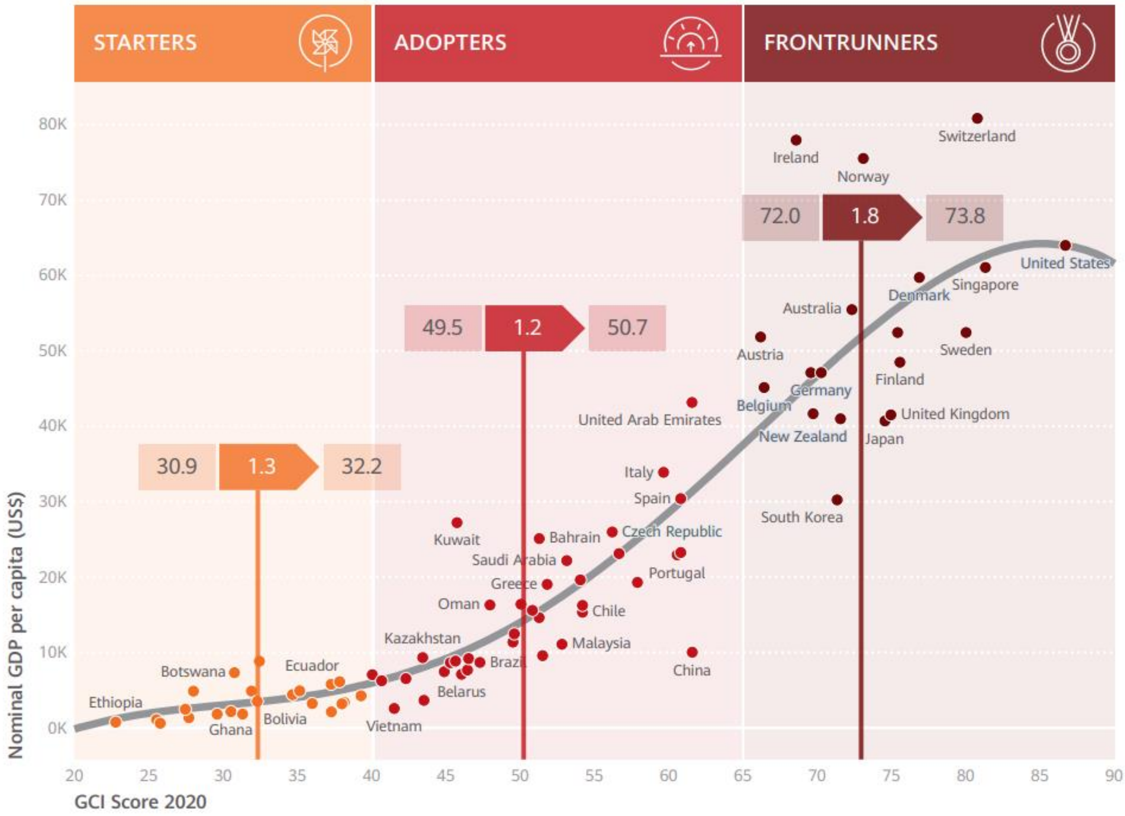


Figure 9. GCI Score 2020 vs GDP per capita. Source: Huawei [105].

Regarding the maturity of the Automated Vehicle technologies, in May 2020 it was revealed that the Audi A8 was no longer including SAE Level 3 features because of the difficulties in getting regulatory approval, as well as the already mature life cycle of the targeted model [106]. It turns out that Honda won the world-first commercial approval for a SAE level 3 car –Honda Legend luxury sedan in Japan– in November 2020 [107]. However, in March 2021 it was announced that just 100 units would be produced of that model, only available for leasing [108] [109]. Mercedes-Benz is attempting to get new S-Class certified as SAE level 3 in the second half of 2021 [110].

3.3.1. Digital Infrastructure

The automated vehicle needs an accurate positioning to ensure road safety. The vehicles utilize several independent positioning methods, such as satellite positioning, inertial positioning, mobile phone network positioning as well as car sensors and HD maps [102]. Nevertheless, the necessary accuracy is only possible by satellite positioning when supported by RTK (Real-Time Kinematics) land stations. Therefore, the digital infrastructure needed by the automated vehicles is the network RTK positioning methodology as a mean to obtain high accuracy GNSS-based positioning in real-time using GNSS carrier-phase data [111].

In this context, tunnels are a challenging scenario as they usually present low GNNS signal coverage. To address such limitation, some studies have presented some innovative solutions: (i) use of LED lighting [78], (ii) GPS, Lidar, and derivative data fusion [79], (iii) landmark-based local positioning system [80], and (iv) C-V2X positioning systems [81]. However, further research in this field is required to stablish standardized solutions and consistent with automated vehicles' capabilities.

Furthermore, High-Definition Map (HD Map) helps localization, detection, prediction, and planning of Automated Vehicles in combination with GNSS and Inertial Measurement Unit (IMU) sensors. Many map providers and OEMs are developing HD Maps with centimeter-level precision. However, there are no open standard ways well-established to produce HD Map at the present time. The creation of HD Maps involves five key steps, which are: (i) Mobile Mapping System (MMS) survey using LiDAR, (ii) 3D plotting, (iii) Feature attributes editing and road network topology building, (iv) Format conversion, and (v) Quality assurance [112].

Shin et al. [113] developed a new localization algorithm based on HD map and ADAS environment sensors to address lane positioning in the absence/limitation of road markings. To do this, the authors improved the accuracy of localization with other road features included in the HD map, such as guardrails.

The HD maps are evolving as Dynamic Map including four geographical information layers: (i) dynamic information, (ii) semi-dynamic information, (iii) semi-static information, and (iv) static information. HD map is referred to the static information part. Dynamic information, semi-dynamic information, and semi-static information are information that changes depending on the surrounding traffic conditions, weather conditions, work zones schedule information, etc., but road surface information, lane information, road structures with 3D coordinates are the map that summarizes information that does not change from time to time [112].

Highly automated vehicles need to monitor everything taking place on the route ahead, even beyond the range of their sensors. Connected and automated vehicles with their sophisticated sensing systems are also part of the solution, providing high-quality information of the conditions, traffic status and incidents that they encounter while driving. Nevertheless, the quality of traffic information needs to be improved, but it will be gradually enhanced with increased fleet penetration of connectivity and high-level automation [102].

They need basically two types of information systems. Firstly, real-time information on incidents, roadworks, events, congestion, and other disturbances on the route ahead as preview information of problems outside the range of the vehicle sensors. Secondly, the rules and regulations of any restrictions ahead concerning automated driving, including real time traffic management information, and dynamic geofencing information in order to avoid routing through forbidden areas.

There are two ways for communication of the digital traffic information and regulations to road users: for CAVs by service providers using connectivity; and for drivers via VMS, as currently. The automated driving systems would also benefit from a harmonized, consistent use of the pictograms by the different stakeholders, but preferably the whole message content.

Automated vehicles need real-time information about the traffic status on the road network, just for both the current status and predicted status of the traffic performance. For the last information, the concept of virtual transport system or a digital twin of the transport system as an element of the digital infrastructure could be very valuable [102]. The use the digital twins in traffic management to simulate the impacts of various traffic management measures to identify the optimal measure in real time, or in fleet management to simulate the impacts of various route alternatives to specific vehicles or transports to choose the best ones, will increase safety and performance.

3.4. Integration of CAVs in the Road Network

A proper Smart Roads Classification system should consider the limitations of the interaction between Connected and Automated Vehicles (CAVs) and road infrastructure. To this regard, the analysis of the literature review shown in sections 3.1, 3.2, and 3.3 allowed us the identification of the most common criteria used for road classification and, in addition to this, the determination of the limitations of current CAVs.

In this context, it is important to distinguish between the concepts of Operational Design Domain (ODD), Level of Service of Automated Driving (LOSAD) [7], and Infrastructure Support Levels for Automated Driving (ISAD) [4].

3.4.1. Operational Design Domain (ODD)

1.1.1.1 3.4.1.1. Concept

According to the SAE J3016, an ODD refers to 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" [5].

Therefore, an ODD summarizes the conditions for which a driving automation system is designed to operate. This definition includes some general categories, but not in a comprehensive way. The same document recognizes the low detail in the definition, given the wide range of possible features that may exist in each level.

This was the first ODD definition for driving automation systems. Further definitions, interpretations, and clarifications do exist in the literature. The British Standards Institution (BSI) developed a taxonomy for Automating Driving Systems (ADS) [114], for which the ODD definition perfectly matched the one provided by the SAE. They, however, specified in the same document that "the ODD comprises the static and dynamic attributes within which an ADS is designed to function safely". As we can see, they distinguish between static and dynamic aspects, and include a very important connotation: "safely".

This is in line with the definition provided by Waymo: "the conditions under which a self-driving system can safely operate" [115]. This corporation specifies that the "Waymo's operational design domain is defined by elements such as geographies, roadway types, speed range, weather, and time of day". In this case, safety is ensured by enforcing that "each vehicle does not operate outside of its approved operational design domain".

Therefore, an Operational Design Domain can be defined as a road section that meets some characteristics that allow the driving automation system to perform. Many of these characteristics refer to the roadway type, road infrastructure, some others refer to the environment, traffic conditions, maximum speed attainable by the driving automation system, etc. These factors also involve variable –i.e., non-static– parameters. Given the early stage of ODDs awareness and implementation by industry, it might be easier to define them by referring to the limitations, i.e., the conditions that are out the ODD.

Figure 10 represents how, for a given vehicle, different ODD-compliant road sections are generated at the zones where all factors comply with the ODD specifications. If just a single factor exits its definition zone, the ODD ends.

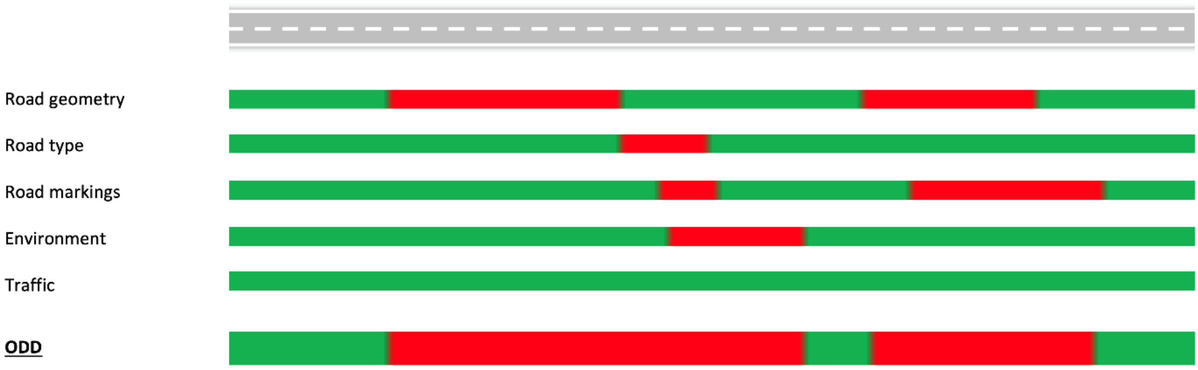


Figure 10. Example of three ODD-compliant zones (for a given vehicle) are generated at the locations where all factors which define the ODD are met (factors are just examples and have been simplified).

In Figure 10, several ODD zones exist for a single road segment. Nowadays, this is a very common scenario, given the limited technology and the lack of clear ODD specifications. In the future, as technology evolves and ODDs are more clearly defined, these zones will tend to be more robust, large, and cover longer itineraries (in the end, it will help extend the use of automated vehicles).

1.1.1.2 3.4.1.2. Taxonomies

To foster the expansion and implementation of ODDs, it is necessary to give a better, more detailed compendium of all parameters and thresholds that might intervene, i.e., a taxonomy.

There have been recent efforts in that direction. A first official approach for ODD taxonomy was introduced by the British Standard Institution, which considered three main attributes: (i) scenery, (ii) environmental conditions, and (iii) dynamic elements [114] (Figure 11).

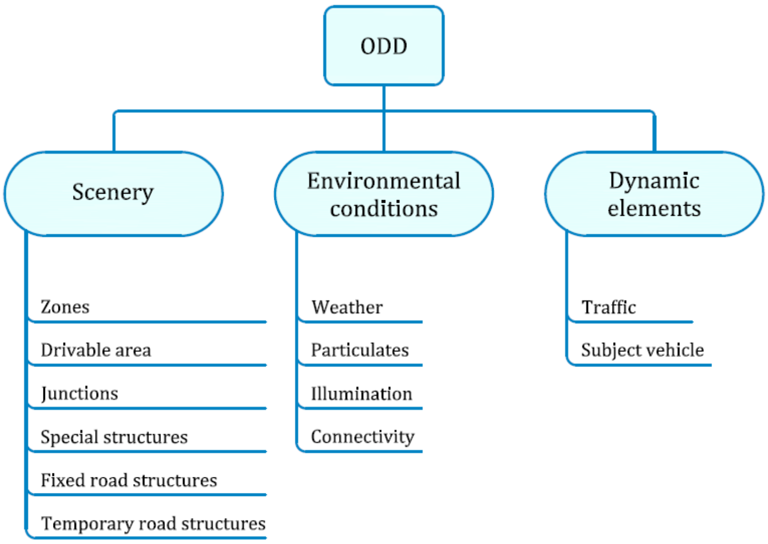


Figure 11. ODD taxonomy by the British Standard Institution. Source: British Standards Institution [114].

The scenery layer refers to the non-movable elements, and is classified into the following attributes:

- Zones. Special road configurations that may differ from typical conditions for driving, or areas with specific regulations. Some examples are traffic management zones, school zones, states, interference zones, etc.
- Drivable area. It refers to every surface that can be used by the ADS to drive. Additional properties such as the drivable area type, geometry, lane, signs, etc. are also included in the

taxonomy. It is worth to indicate that this section includes all parameters related to road geometrics, but with little detail (Figure 12) (e.g., just two attributes are given for the horizontal plane: straight lines and curves; or level plane without distinguishing crest and sag vertical curves).

- Junctions. These are classified into roundabouts (normal, compact, double, large, and mini) or intersections (T-junctions, staggered, Y-junctions, crossroads, and grade separated). A signalized/unsignalized category exists for all types of roundabouts.
- Special structures, classified as automatic access control, bridges, pedestrian crossings, rail crossings, tunnels, and toll plazas.
- Fixed road structures, like buildings, streetlights, street furniture, and vegetation.
- Temporary road structures. These might be placed on the road due to local requirements or accidents, temporary affecting the regular visibility and performance. The following attributes are suggested: construction site detours, refuse collection, road works, and road signage.

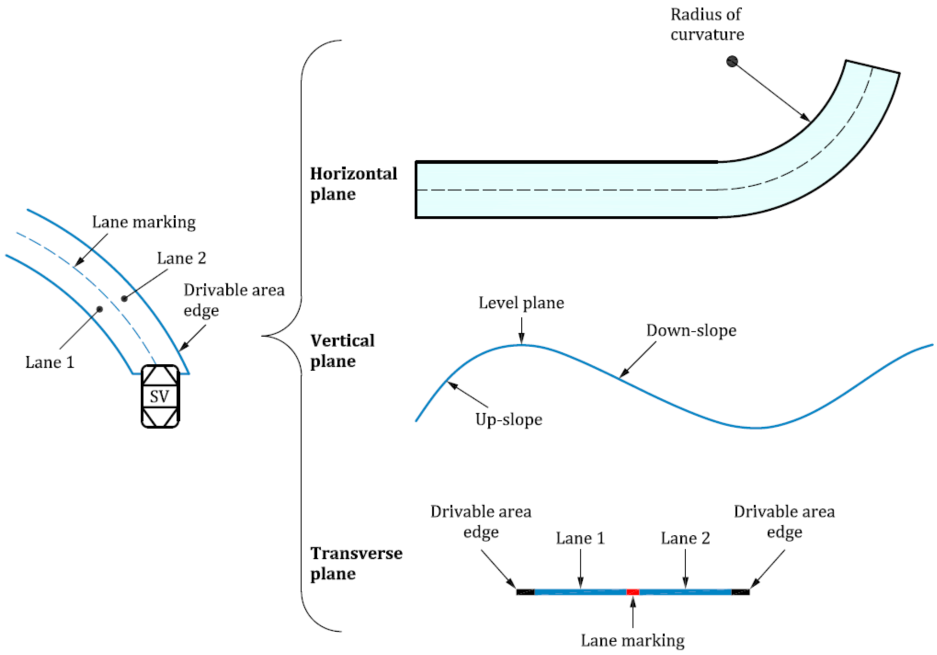


Figure 12. Drivable area geometry configurations, provided by the British Standard Institution. Source: British Standards Institution [114].

The environmental conditions layer refers to weather and atmospheric conditions. Some of them present high degrees of variability, so further work on this translation to ODDs is required. It is structured into the following attributes:

- Weather, including wind, rainfall, and snowfall.
- Particulates (obscuration by non-precipitating water droplets and other particulates). This attribute also includes marine, non-precipitating water droplets or ice crystals (e.g., fog), sand and dust, smoke and pollution, and volcanic ash.
- Illumination. This includes natural and artificial illumination, in the following categories: day (also indicating elevation of the sun above the horizon, and its position), night or low-ambient lighting, cloudiness, and artificial illumination (e.g., streetlights or oncoming vehicle lights).
- Connectivity. It refers to the ability of a vehicle to receive data from and/or transmit data to an external system to determine positioning or to communicate with other vehicles and the

wider infrastructure. This parameter is becoming more and more important. It is composed of the following attributes: communication (V2V/V2I) and positioning. V2X can also be included in this category. Signal strength and interference are suggested as sub-attributes.

The dynamic elements layer refers to the movable objects of the ODD. It is structured as follows:

- Traffic. This attribute also includes density of agents, volume of traffic, flow rate, agent type (eventually including Vulnerable Road Users and animals), and presence of special vehicles. Parked and stationary vehicles might also be included in this layer.
- Subject vehicle. It refers to the properties of the vehicle itself. The speed is suggested as an important factor to be considered in the ODD. Stakeholders might be willing to include additional behavior capabilities, such as ability to change lanes, etc., as part of the ODD definition.

The European ITS Platform (EU EIP) [102] developed another taxonomy, differentiating between (i) physical infrastructure, (ii) digital infrastructure, (iii) communication infrastructure, and (iv) infrastructure operations and maintenance.

The physical infrastructure layer distinguishes the following attributes:

- Roadway type, including details and context. This identifies the type of road (such as motorways, highways, etc.). The details and context refer to road geometry and sight distances, which might be adapted to host automation.
- Special sections, such as tunnels, bridges, toll plazas, etc. These sections might need specific equipment and require differential performance of vehicles.
- Lanes and carriageways. The lane width becomes critical for pavement maintenance, as well as to ensure that vehicles can perform. In addition, authorities might want to dedicate specific lanes for automated vehicles.
- Shoulders and kerbs. Particular configurations might be adapted for stopping SAE level 3 or 4 vehicles. Their specific configurations should be implemented in the ODD.
- Pavements. Vehicle positioning and truck platooning will have an impact on pavement durability and maintenance.
- Road markings. Their configuration becomes critical to host automation. Harmonization is highly encouraged across countries.
- Intersections and connections. This category includes interchanges, intersections, driveways, and weaving sections.
- Traffic signs. Like road markings, traffic sign harmonization is highly encouraged. In addition, not all signs provide valuable information to automated vehicles, as well as new signs might be developed to assist automation.
- Road equipment or furniture. This category includes landmarks (which have to be identified and located by the vehicles), passenger pick-up/drop-off points for some use cases, specific lanes for freight vehicles, and game fences.
- Facilities for vulnerable road users, orientated to segregate traffic from automated vehicles.
- Speed range. Speed ranges are expected to vary, to be adapted to existing speed limits.

The digital infrastructure category includes four attributes, some of them with no further detail due to the lack of standardization or the maturity level of the associated technology:

- Positioning. This attribute should indicate the available systems and their accuracy.

- Traffic information system. This information becomes more important with the automation level. Two kinds of information systems are proposed: real-time information on incidents, roadworks, events, congestion, etc.; and information about rules, regulations, and restrictions on automated driving.
- HD maps. Very accurate maps are required to extend ODDs and share microscopic information about traffic performance.
- Traffic performance status on road network. This information will be used to inform the drivers, and to predict future situations.

The communication infrastructure is not separated into subcategories. The document indicates that it is evolving very fast. There are many options nowadays, including Roadside Units (RSU) for short-range communications, and cellular connections for long-range.

Regarding the infrastructure operations and management, the categories are detailed as follows:

- Traffic management and control. This attribute is expected to have its highest impact when specific road facilities are segregated for automated vehicles. Special attention should be given to ODD terminations.
- Incidents and events. Expected for the medium and long term, it should share the information of the incident (and its finalization) more efficiently than today.
- Road works. These should be marked in a way that is easily recognized by automated vehicles. A huge effort in standardizing how road works are indicated should be undertook.
- Infrastructure maintenance. These operations would benefit from a new source of information: automated vehicles reading the road status and transmitting it to the infrastructure, to see its evolution and plan interventions.
- Fleet supervision. In some cases, regulations are expected to require remote supervision and control of some vehicles externally. This also requires defining which parts of the network might be externally supervised or controlled.

In 2020, the Society of Automotive Engineers (SAE) released a report with a conceptual framework of ODDs [116]. This framework focuses on the physical road infrastructure including its geometry, the environment, and the behavior of other road users. OEMs are encouraged to explicit and make public the factors supporting/limiting their ODDs. The following factors are proposed:

- Weather- and climate-related environmental conditions.
- Surface road conditions.
- Operational restrictions, i.e., other aspects within the operational environment not related to the first category.
- Road users.
- Non-static obstacles on the road.
- Connectivity to other road users, infrastructure, and traffic management centers.

Other approaches have been arising very recently, although the only one with the rank of standard to this day is the proposed by the BSI. Standard ISO/AWI 34503 on Road vehicles – Taxonomy for Operational Design Domain for Automated Driving Systems is currently under development [117]. Another interesting initiative in progress is OpenODD [118], which tries to propose a clear syntax to define ODDs, accessible by OEMs, road authorities, users, etc., who can define, edit, and read ODDs using a simple format.

1.1.1.3 3.4.1.3. Limitations

The most remarkable limitation to ODDs is that these have been defined from the point of view of the vehicle, and every single vehicle (or model) will have its unique –and time varying– ODD. Therefore, a road segment being drivable by an automated vehicle is not a property given or managed by the road authority/operator, but a varying characteristic of every single automated vehicle.

The lack of a standardized definition of ODD hinders OEMs to explicit their ODD constraints. In the end, this makes it more difficult for road administrators to be aware of which road segments are more adequate for automation.

In addition to the elements that an ODD taxonomy should include, thresholds for these elements should be applied too (e.g., minimum radius compatible with automation for a certain speed; minimum road marking width, etc.). These thresholds should be robust, i.e., they should ensure that a vehicle lying within the ODD range would not release control triggered by this factor.

ODDs are very likely to depend on the speed of the vehicle, as demonstrated by García et al. [7]. These researchers designated the maximum speed attained without releasing control to the driver as “automated speed”, which is highly dependent on the vehicle technology. How the speed affects ODDs requires further research, especially to detect interactions among factors that may reduce the ODD extension beyond the limits of the individual ones.

1.1.1.4 3.4.1.4. Interaction with human drivers

Establishing clear ODDs is especially important for SAE levels 3 and 4. For lower levels, the driver is the one responsible for all the driving task, given the relatively frequent disengagements. SAE level 5 is the top level, a vehicle capable of driving anywhere regardless ODDs.

SAE level 4 vehicles are those which can perform the complete driving and monitoring tasks within their ODD. The human driver is not required for the driving or monitoring tasks, so they can completely shift their attention to other secondary tasks –even sleep–. But what happens if the vehicle approaches to the end of its ODD, or it abruptly terminates triggered by a sudden variation of any factor supporting the ODD? These situations should not be a problem for SAE level 4 vehicles, given that in-time warnings to shift to manual, and programmed responses to take the vehicle to a safe condition or location are included in the system.

This is not applicable to SAE level 3 vehicles. On the contrary to SAE level 4, these vehicles can perform the Dynamic Driving Task (DDT) and monitor the environment but cannot guarantee that they will not disengage even within a zone that meets their ODD. Therefore, human drivers must be present for fallback response, to take manual control of the vehicle, if requested. On the contrary to SAE level 2 vehicles, these disengagements are expected to be very infrequent, which will be more comfortable for drivers but more unsafe given that drivers’ attention might be focused on secondary tasks. Thus, resuming control would take longer than for SAE level 2. The SAE J3016 indicated that these vehicles might incorporate systems to reduce the consequences of an unsuccessful takeover, but these are not as smart as for SAE level 4. All these systems are fully described in section 3.4.2.4.

3.4.2. Adaptation of ODD to road infrastructure

1.1.1.5 3.4.2.1. Operational Road Section (ORS)

To facilitate the application and management of ODDs from the road infrastructure side, it is necessary to generalize the concept to a traffic stream with vehicles showing different automation capabilities.

Within a certain road segment, the different vehicles will present specific ODD-compliant sections, generated by different factors (Figure 13).

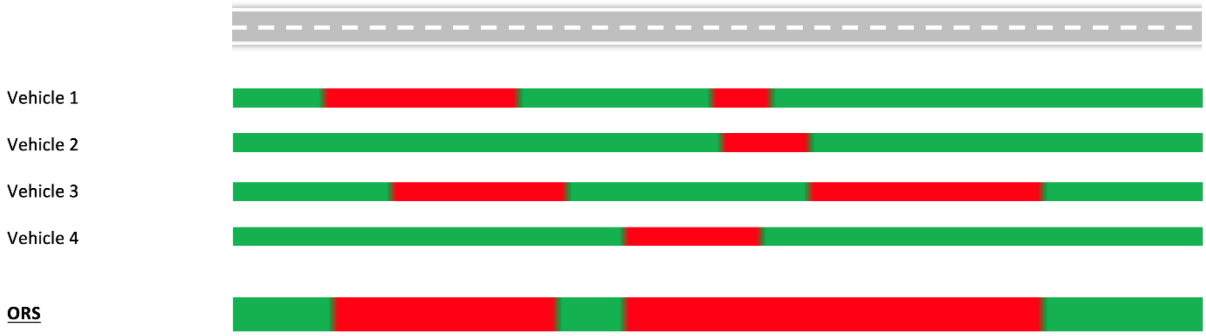


Figure 13. Four vehicles showing different ODD-compliant sections within the same road segment. Their overlapping can be considered an "Operational Road Section" (ORS).

Within the road segment, there will be some sections out of almost all vehicles' ODDs, other sections within all –or most– vehicles' ODDs, and other sections in between. The zones that are ODD-compliant to all vehicles are indeed sections that can be driven autonomously by all vehicles. Knowing this information is very important for road authorities, since they could actively work towards increasing their length and adapting new sections.

These sections are proposed to be called "Operational Road Sections" (ORS). From a practical perspective, an ORS should be established in all zones that match with all vehicles' driving automation systems. It should be noted that these ODDs should be robust enough to prevent disengagements if some of the dynamic factors slightly vary (i.e., ORS should be as static as possible). By making ODDs explicit, ORS would be easier identified, and OEMs could receive feedback from road administrations to improve their systems.

ORSs, like ODDs, will vary in time. At the beginning, only smooth sections at freeways are expected to be supported by all driving automation systems. As the technology evolves, other sections will become compatible with all systems, extending the ORS application. Active adaptation of road sections would accelerate this ORS generalization, but to select the most cost/effective measures ODDs should be made explicit.

1.1.1.6 3.4.2.2. Restricted Operational Domain (ROD)

A vehicle performing within its ODD is expected to have no limitations apart from the capabilities of the system itself. However, the ODD may terminate at some point, either in a planned way (the vehicle reaches an ODD physical boundary) or abruptly (some factor exits the safe zone and terminates the ODD). In both cases the vehicle might be capable of performing a Dynamic Driving Task (DDT) fallback, which is not a regular DDT but provides some capabilities to take the vehicle to a safe stop (please note that not all systems present this capability, more information can be found in section 3.4.2.4) [119].

This situation is called a "Restricted Operational Domain" (ROD): "specific conditions under which a given driving automation system or feature thereof is currently able to function, including, but not limited to, driving modes" [120].

On the contrary to ODDs, the vehicle performance is affected differently depending on which factor activated the DDT fallback. This means that depending on the factor that has restricted application of the ODD, the vehicle may be able to keep performing at ideal conditions, with degraded functionality (e.g., reducing the speed), or even releasing the control to the driver. Routes could be even automatically replanned to meet the vehicle's ROD after a failure.

A very similar concept to ROD is the reduced or conditioned ODD. In this case, the vehicle may foresee a factor which is about to change and terminate abruptly the ODD. Instead of performing a degraded mode (ROD), the driving automation system might adopt some restrictions to the vehicle performance in order to prevent exiting from the ODD. While the definition between both concepts is slightly different, the practical implications are similar. The ASAM OpenODD project is working to integrate the concept of reduced/conditioned ODD [118].

As an example, dense fog may dramatically limit the sight distance of the vehicle sensors. Like a human, the driving automation system may reduce the speed, in order to drive as fast as possible, but ensuring that the vehicle can safely stop, if necessary. In this case, the vehicle can be considered to be within the ODD, with restricted performance.

1.1.1.7 3.4.2.3. Operational Design Condition (ODC) and improved ODDs

A broader concept –Operational Design Condition, ODC– has been recently introduced [121], being composed of three items: the instantaneous capabilities of a vehicle, the ODD, and the driver ability to resume control, if requested.

It becomes also necessary to indicate that ODDs are not something static that remain unchanged along the lifecycle of an ADS. Software updates can bring new capabilities to the ADS –even using the same sensors and hardware– so the ODD can be improved in time. As a result, information about the ODD version should be integrated into the ADS specifications, to accurately match its capabilities to the environment and roadway requests.

1.1.1.8 3.4.2.4. Minimal Risk Condition (MRC)

For every single vehicle, the ODD-compliant sections along a road itinerary are expected to be discontinuous. For SAE levels 3 and 4, the driver is expected to be able to shift to a secondary task while the vehicle is in charge of the DDT. A problem arises under three circumstances:

- The vehicle experiments a failure that stops automation abruptly. This may happen to SAE level 3 and 4 vehicles.
- The Automated Driving System (ADS) fails –which is far more likely to happen to SAE level 3 than 4, where is not impossible but rather rare– and the driver is requested to intervene.
- The ODD approaches to its end, which is already known by the driving automation system. On the contrary to previous situations, the vehicle has more time to plan how to perform and warn the driver.

In all these cases, the Dynamic Driving Task has to be released to the human driver, who might be attentive to a secondary task. Hence, retaking control of the vehicle needs the driver to resume road and traffic monitoring, think about the possible actions, and perform the adequate Dynamic Driving Task. This requires a time that sometimes might not be available. Therefore, ADSs have different planned responses depending on the situation.

The ideal situation is a planned handover. In this case, the vehicle may emit audible, visual, and even haptic warnings, escalated in time, which become very evident if the vehicle nears the ODD exit without human intervention (Figure 14). The ADS does not fully release control to the driver from the very beginning their engagement starts. Instead, the ADS gradually releases control, giving time to the human driver to be fully aware of the environmental circumstances and make sure that the DDT shift is perfectly released [122].

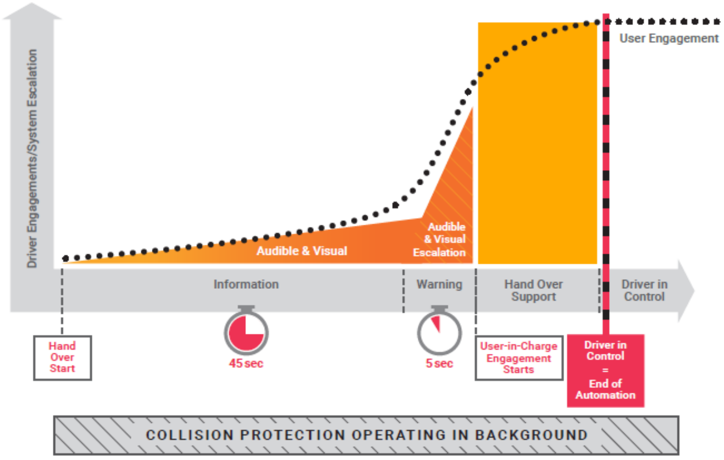


Figure 14. Planned handover with a responsive driver. Source: Thatcham Research [122].

This period of time does not exist for abrupt –unplanned– handovers. In this case, ADSs must skip the gradual escalation of the warnings and directly use the most notorious ones (Figure 15).

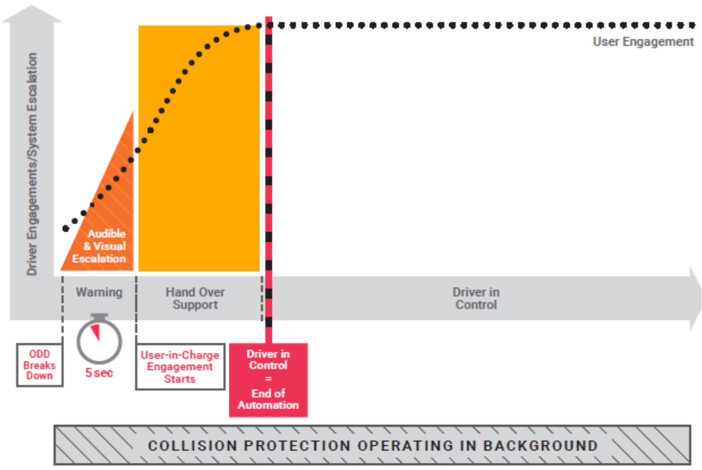


Figure 15. Unplanned handover with a responsive driver. Source: Thatcham Research [122].

An important question is: what happens if the driver is unable to take over control of the vehicle? SAE level 4 and 5 ADSs can take the vehicle to a Minimal Risk Condition (MRC), which is defined as "a condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be completed" [5]. This means that these highly automated ADSs can still control the vehicle with restricted conditions, make a decision, and take the vehicle to a position that minimizes the risk to itself and the rest of road users (Figure 16).

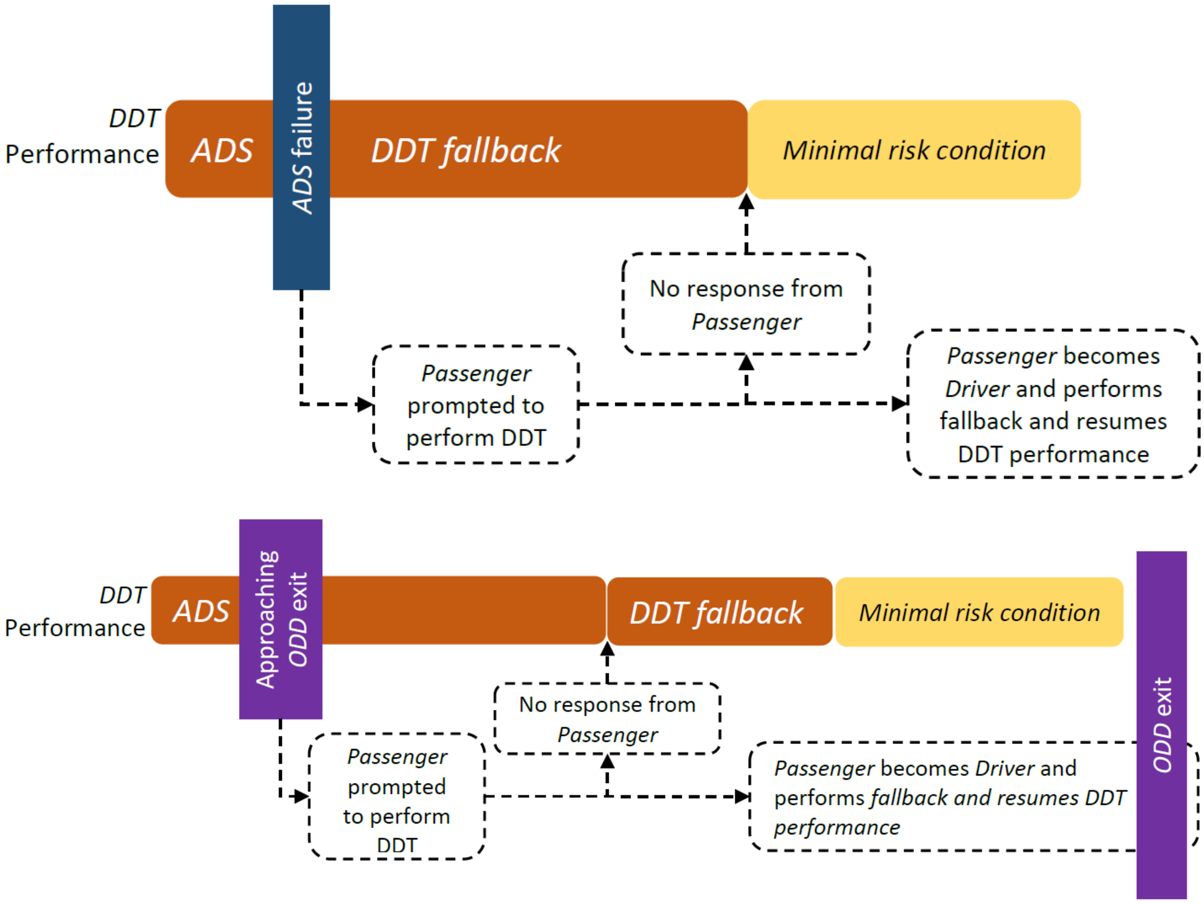


Figure 16. Achieving the MRC in case of ADS failure and ODD exit. The first case applies to level 4 and level 5 ADSs, the second one only to level 4 ADSs. Source: Society of Automotive Engineers [5].

The SAE J3016 establishes that a SAE level 4 and 5 ADS must always be able to reach the MRC under all circumstances. This makes a difference with a SAE level 3 ADS, which may have some DDT fallback responses to reach an MRC under some circumstances, but not all. Moreover, the SAE J3016:2018 does not establish a minimum requirement to a SAE level 3 ADS performance if the driver is unable to respond. In its section 8.6, this document indicates that SAE level 2 and 3 driving automation systems "may have an additional failure mitigation strategy designed to bring the vehicle to a controlled stop wherever the vehicle happens to be". This mitigation strategy cannot be considered an MRC, since it just controls the vehicle to reach a sudden stop (Figure 17).

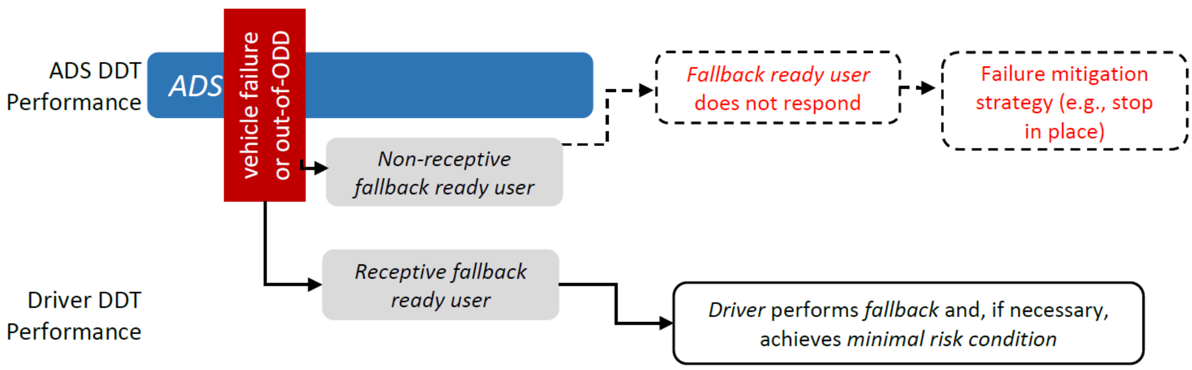


Figure 17. Failure mitigation strategy for SAE level 2 and 3 driving automation systems. Source: Society of Automotive Engineers [5].

ADSs for levels 4 and 5 may also have this feature, which should only activate upon very rare cases, such as catastrophic failure conditions that completely exceed the ADS capacity.

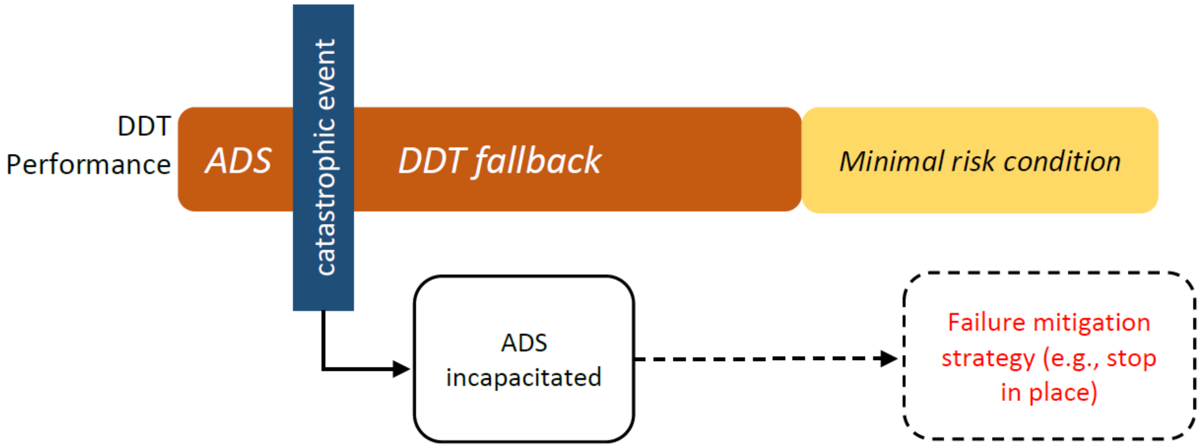


Figure 18. Failure mitigation strategy for SAE level 4 and 5 ADSs (source: Society of Automotive Engineers [5].

How the ADSs implement these strategies varies significantly across models, ODD types, and technology. Preparing the vehicle for an MRC also varies across ADSs (Figure 19). In fact, given the low regulatory enforcement and the high variability, the World Economic Forum encourages OEMs to detail how the vehicles would respond in case of planned/unplanned takeovers [123].

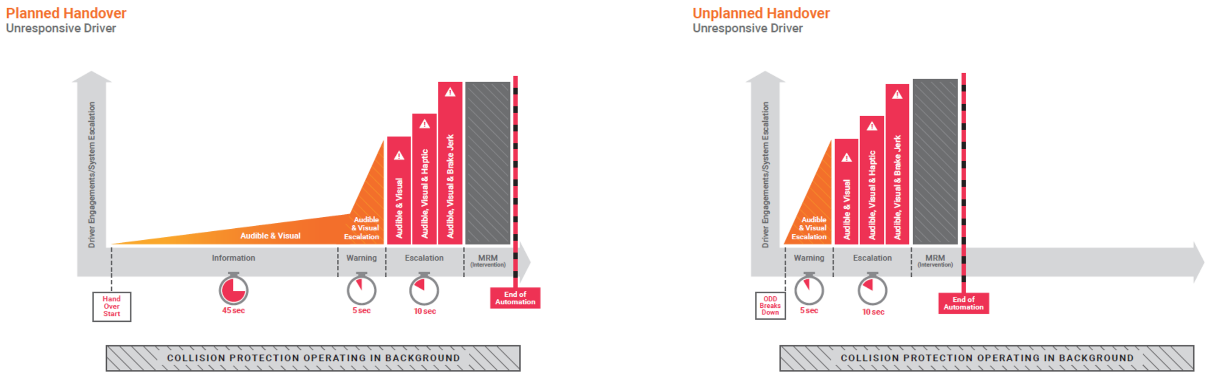


Figure 19. Handover examples for unresponsive users for a planned ODD exit (left) and an abrupt release (right) (source: Thatcham Research [122].

An MRC is a final state, i.e., the objective to reach by the ADS when needed. From the regular performance to the MRC, a maneuver has to be undertook (Minimal Risk Maneuver, MRM), which should also be considered to minimize the risk condition. In fact, the ADS may balance several options with diverse risk conditions, finally performing the one that presents the lowest risk in combination with the maneuvers [124].

As an example, a vehicle performing at the left lane of a freeway that requires an MRC could balance several options, such as stopping on the left shoulder, on the right shoulder, keeping the vehicle moving slower on the right shoulder to reach the nearest exit ramp, etc. Stopping the vehicle in the right shoulder might be the optimum option under low traffic volume situations, but might not be the case if the high traffic volume makes lane change too dangerous, or the vehicle radar triggered the ADS malfunction.

The MRM is planned ad hoc as a function of the environment conditions and why the MRC was requested. Once the MRC has been identified, the MRM is generally divided in two stages [124]. First, the vehicle reduces its speed on the lane to facilitate the stopping maneuver, and/or to require less sight distance. This speed may affect traffic performance but should be still compatible in order to not be a safety hazard to other users (e.g., 30 km/h). In the second stage, the ADS maneuvers the vehicle to reach the safe stop. If possible, this stop takes place outside the main roadway (e.g., at an exit ramp). If this is not possible, other option is to stop the vehicle on the shoulder.

1.1.1.9 3.4.2.5. Application to road infrastructure

Awareness of Operational Road Sections can be very important to road administrations in order to improve traffic safety and performance. From the first moment when ODDs become explicit, road administrations should work towards reducing heterogeneity in their road networks, which will create larger ODD-compliant regions with most vehicles. Especial attention should receive the sections which are within the ODD of all vehicles (i.e., Operational Road Sections). Long ORSs are expected to present the highest standards in safety and performance, as well as work towards increasing user acceptance of automation.

Road infrastructure should be updated in order to facilitate minimal risk conditions –and minimal risk maneuvers–. Some alternatives have already been proposed, such as hard shoulders, emergency refuge areas (ERA), and parking lots at interchanges or exit ramps (Figure 20) [125] [126]. These facilities provide from continuous to less frequent opportunity to reach an MRC, but with increasing safety levels.

Figure 20. Interchange adapted to host automated vehicles which require an MRC (safe harbour). Ssource: Highway Engineering Research Group, UPV.

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3.4.3. ODD implementation roadmap

1.1.1.10 3.4.3.1. Extending the ODD definition

The definition of ODD provided by the SAE in 2018 was not comprehensive but necessary, given the lack of implementation at the moment. Nowadays, the development and deployment of CAVs has reached a point in which a more comprehensive taxonomy should be provided, in order that OEMs and TIER1s explicit the conditions that are supported by their driving automation systems.

The oncoming ISO 34503 would work in this direction. By explicating ODDs, road administrations and operators could also work in: (i) harmonizing road facilities to be supported by more ADSs and (ii) indicating OEMs and TIER1s the specific needs for the ADSs to come.

Some private initiatives have worked on this direction, such as the Roadcheck utility developed by TomTom for their HD maps [127]. This feature matches the road infrastructure information with every driving automation system capabilities, determining whether automated driving can be safely enabled or not, even at ramp exits, merging segments, etc. (Figure 21).

Figure 21. Example of the Roadcheck utility developed by TomTom [127].

Not only has this utility been developed to provide valuable information about automated driving to users, but it also facilitates OEMs the introduction of the ODD-compliant sections, even using information coming from real disengagements.

Comparing road sections with disengagement patterns is especially relevant in order to verify to what extent the proposed ODDs are robust and match the definitions provided by OEMs. Road administrations and operators could also use this information to propose ORSs that meet most –if not all– existing ODDs.

It is important to highlight that the driver (either human or vehicle) is the ultimate responsible for the driving task. Therefore, road administrations and operators should make explicit the available automated driving supporting road characteristics for every road segment and the automated vehicle will decide if it can switch on automated driving or not, according to the technologies it is equipped with.

1.1.1.11 3.4.3.2. User acceptance

Users would probably be the most benefited from improving automation, due to a better traffic performance and safety levels. However, these aspects may not be very evident for the lower automation levels. In addition, some existing SAE level 2 vehicles may present frequent disengagements that discourage drivers from enabling them. This may be caused because drivers are often unaware about the possibilities of their vehicle's driving automation system. Therefore, it becomes very important to foster drivers' acceptance, by informing them about what their vehicle can do (e.g., platforms like https://mycardoeswhat.org [128]), as well as informing them about the engagement/disengagement status. In this case, an on/off indicator is not sufficient and should be replaced by more continuous feedback.

Very frequent disengagements are disappointing for drivers, who are likely to disable the system. On the contrary, very distant disengagements may be unsafe, if drivers stop being attentive to the road. Therefore, to increase user acceptance, vehicles should: (i) clearly indicate the zones where frequent disengagements are expected, so they are recommended to disable the driving automation system, and (ii) target as soon as possible all ODD terminals, shifting to plan all handovers as possible. TomTom's Roadcheck feature works in this direction.

1.1.1.12 3.4.3.3. Enhancing connectivity

Connectivity, HD maps, and digital infrastructure become especially important for SAE level 3+ vehicles. On the contrary to SAE level 2 systems, the vehicle must be aware of the specific road/environment conditions in order to compare them to their ODD constraints. Among the information sets that can be provided, the following two are of major importance: (i) static and dynamic road/environment conditions, including –if available– traffic data to support performance and (ii) relevant infrastructure features that could be used for MRC. Special attention should be given to all ODD factors, and the ODD entrance/exit zones.

Improving V2X also works in making unplanned handovers safer. By sharing information among vehicles and the infrastructure, information about incidents and other events can be shared to distant approaching vehicles, which could ask drivers to stay aware of a potential request to intervene.

1.1.1.13 3.4.3.4. Level of Service for Automated Driving (LOSAD)

The Level of Service for Automated Driving (LOSAD) is a concept recently introduced by García et al. [7] to indicate how ready a road segment is to host automation. Like any other Level of Service (LOS), it ranked the road segment from E –minimal automation support– to A –automation fully supported.

Having such a direct indicator to reflect the automated-readiness level is very important for road administrations and operators. Road networks could be ranked as a function of LOSAD. Traffic volume could also be compared to it. These charts could be used to prioritize actions and/or assess the status of a road network. In fact, the LOSAD A road segments would be those identified above as Operational Road Sections –i.e., road sections that are fully compatible with automation– for a sufficient road segment length (thresholds still to be determined).

LOSAD B to E present different extensions and frequencies of ORSs. For instance, LOSAD B may be a segment that presents relatively long ORSs interrupted with a few non-ODD compliant zones for some of the automated vehicles. LOSAD E may be the case of very short ORSs that almost prevent enabling automation. Thresholds and specific characteristics of every level are still to be determined.

Since LOSAD should be based on Operational Road Sections, a very deep knowledge about factors affecting ODDs is required. Otherwise, ODDs should be evaluated for every single vehicle and finally aggregated for the whole road segment. Figure 22 shows how the LOSAD could be determined for a single vehicle. The lower part of the figure represents the engagement (green) and disengagement zones (red) for a given driving automation system. This could be transformed into a time-space diagram (top), computing how frequent these disengagements are. The aggregation for the whole road segment means the determination and analysis of the ORSs as the Figure 13 shows.

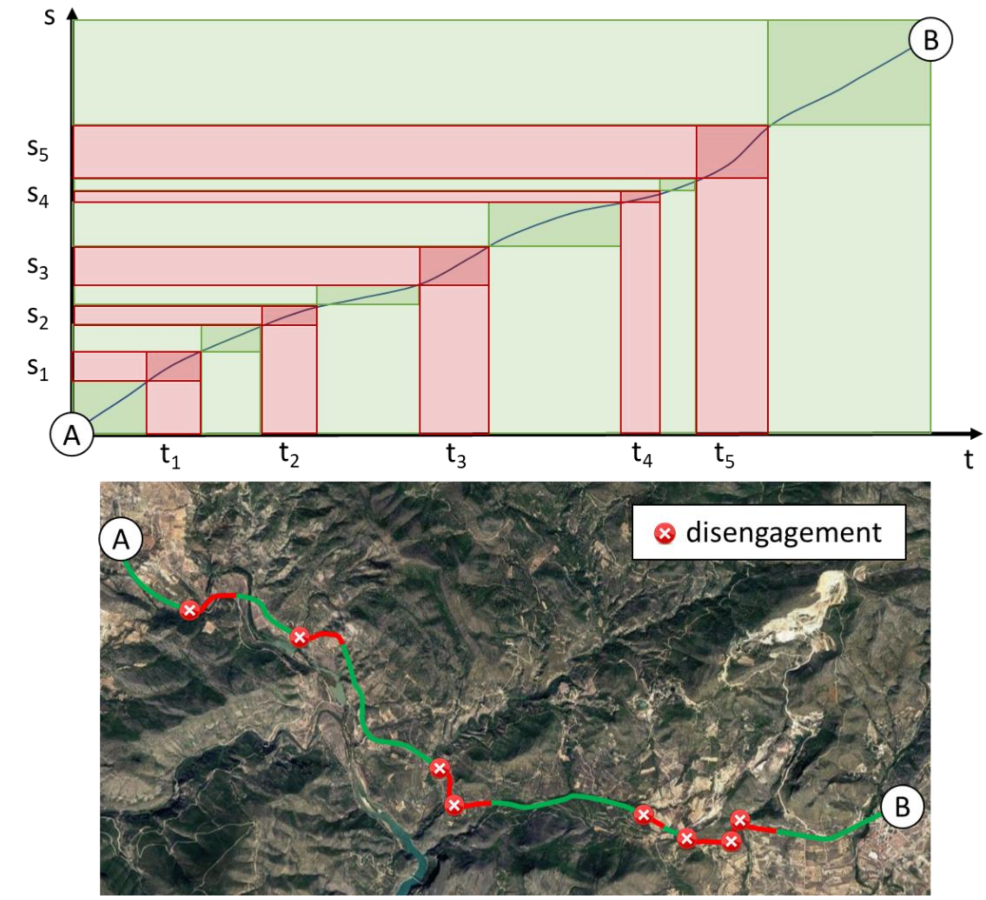

Figure 22. Concepts of ODD and LOSAD.

Another indirect way of determining the LOSAD might be through disengagement reports from marketed vehicles. By geotagging all disengagements –and, if possible, the triggering conditions– HD maps could continuously be updated in order to indicate which road segments are more likely to disengage certain driving automation systems. This information could even distinguish the different systems, which are likely to present different disengagement patterns. TomTom's Roadcheck feature (or similar approaches) could evolve to incorporate LOSAD in this direction.

The LOSAD concept, despite still requiring further refinements upon the information that finally becomes available, is a complementary parameter to ISAD [4]. LOSAD describing how vehicles' ODDs interact with the road infrastructure, and ISAD indicating the connectivity capabilities, establish a sound basis to foresee how Connected and Automated Vehicles are likely to perform along a road network.

3.5. Safety considerations of CAVs

The implications of automated driving on safety can be analyzed at diverse levels [129]: (i) vehicle, (ii) transportation system, and (iii) society (Figure 23). At a vehicle level, Connected and Automated Vehicles (CAVs) can be examined by means of their contribution to the critical driver-related reasons for crashes, such as distractions, inattention, or performance error. At a transportation system level, a reduction in the number of traffic conflicts and crashes is expected with CAVs. At a society level, crashes are one of the main health concerns and the health impacts of CAVs can be studied by comparing crash occurrence under different Penetration Market Rates (PMR), including the scenario with only human-driven vehicles. Although traffic crashes caused by driver error are expected to be eliminated after CAVs deployment, other safety issues may compromise the positive impacts: (i) system operation failure, (ii) cybersecurity, (iii) users' riskier behaviors, (iv) increasing traffic flow, (v) mix-traffic issues, and (vi) inequity in impacts and ethical issues if only wealthy consumers could afford CAVs as personal vehicle (Figure 23). Obviously, these safety implications depend on the automation levels of the CAVs available on the market.

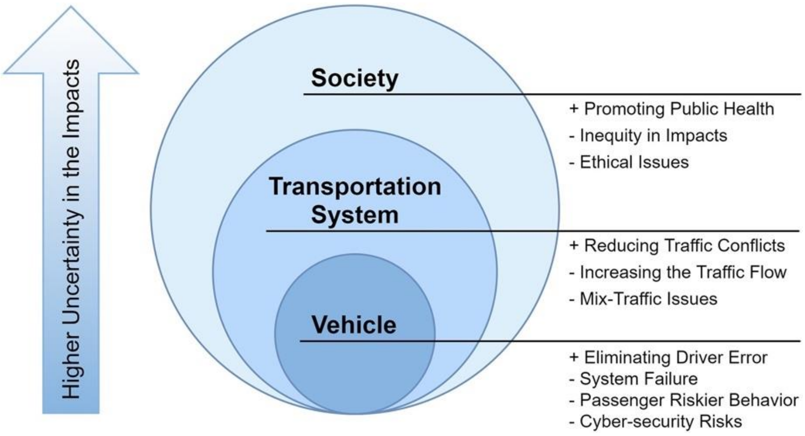

Figure 23. Impact of automated driving on safety [129].

Sohrabi et al. [129] stablished a total of six CAVs safety quantification approaches (Figure 24):

- Target crash population.
- Road test data analysis.
- Traffic simulations.
- Driving simulators.
- System failure risk assessment.
- CAV safety effectiveness.

The target crash population approach can be used to estimate the number of preventable crashes for assessing CAV safety at the transportation system and society levels. The corresponding quantification process commonly follows three steps [130] [131]: (i) identify CAVs' ADS and ADAS functionality, (ii) match CAV functionality with the target crash type, and (iii) explore the crash datasets and identify preventable crashes.

Road test data analysis can also be used for assessing CAV safety at the transportation system and society levels. Particularly, this approach presents three types of analyses: (i) comparison between CAV incidents and conventional car crashes, (ii) characterization of CAV crashes in terms of collision type, crash location, speed, and causes of the crash, and (iii) safety reliability of CAVs. An important shortcoming linked to these analyses is the great disparities in the equivalence between CAV and conventional vehicle crash rates which made the conclusion interpretation harder [129]. Furthermore, rate of rear-end crashes was found to be higher in CAV crashes [132] [133] [134], while the severity of crashes was found to be lower [132]. To this regard, the likelihood of CAV crashing decreases with the number of lanes marked a centerline and clear weather conditions. Banerjee et al. [135] studied the cause of CAV disengagement concluding that 64% of disengagements were the result of problems in, or untimely decisions made by, the machine learning system.

Driving simulator and traffic simulation studies can be used for evaluating CAV safety in terms of Surrogate Safety Measures under different implementation scenario. While driving simulators were commonly used at the vehicle level –e.g., to investigate disengagement from Automated Driving

Systems (ADS)–, traffic simulations were used at the transportation system –e.g., to study interactions between CAVs and other types of vehicles–. Most simulations studies explored the influence of CAV MPRs on safety by determining different Surrogate Safety Measures (SSMs), being the most commonly used time-to-collision (TTC) and post-encroachment time (PET). Most previous research concluded that the number of near-miss events decreased as the CAV MPR increased. However, some studies observed the opposite effect, i.e., an increase in the CAV MPR resulted in an increase in the number of traffic conflicts [136] [137].

The studies based on driving simulators can be divided into: (i) vehicle-human interaction (take-over situations in different driving states, such as drunk driving, drowsy driving, distracted driving, unplanned disengagement from the ADS, planned disengagement, etc.), and (ii) vehicle-vehicle interaction (joining a conventional vehicle to a platoon of CAVs). Regarding vehicle-human interaction studies, automated driving would negatively affect a take-over scenario in response to a risk while the vehicle is disengaged from the ADS [138] and increase driver drowsiness [139] compared to manual driving. Moreover, drivers of conventional vehicles presented a more aggressive driving behavior when joining a platoon of CAVs as the MPR increased and the time headway of CAVs decreased [140].

The system failure risk assessment approach aimed at evaluating CAV safety at the vehicle level based on the system components' failure rates. Malfunctioning sensors in object recognition, misinterpretation of data, and poorly executed responses can compromise CAVs' reliability and lead to major safety consequences in an automated environment [141].

Finally, CAV safety effectiveness approach was used to analyze the implications of Advanced Driver Assistance Systems (ADAS) on safety, providing insights at both the transportation system and the vehicle level. To this regard, Wang et al. [142] studied the safety effectiveness of nine ADAS and ordered them in descending order as follows: intersection movement assists, pedestrian collision and mitigate (PCAM), lane departure warning (LDW), lane change warning (LCW), forward collision warning (FCW), electronic stability control (ESC), blind-spot warning, automated emergency braking (AEB), and adaptive cruise control (ACC).

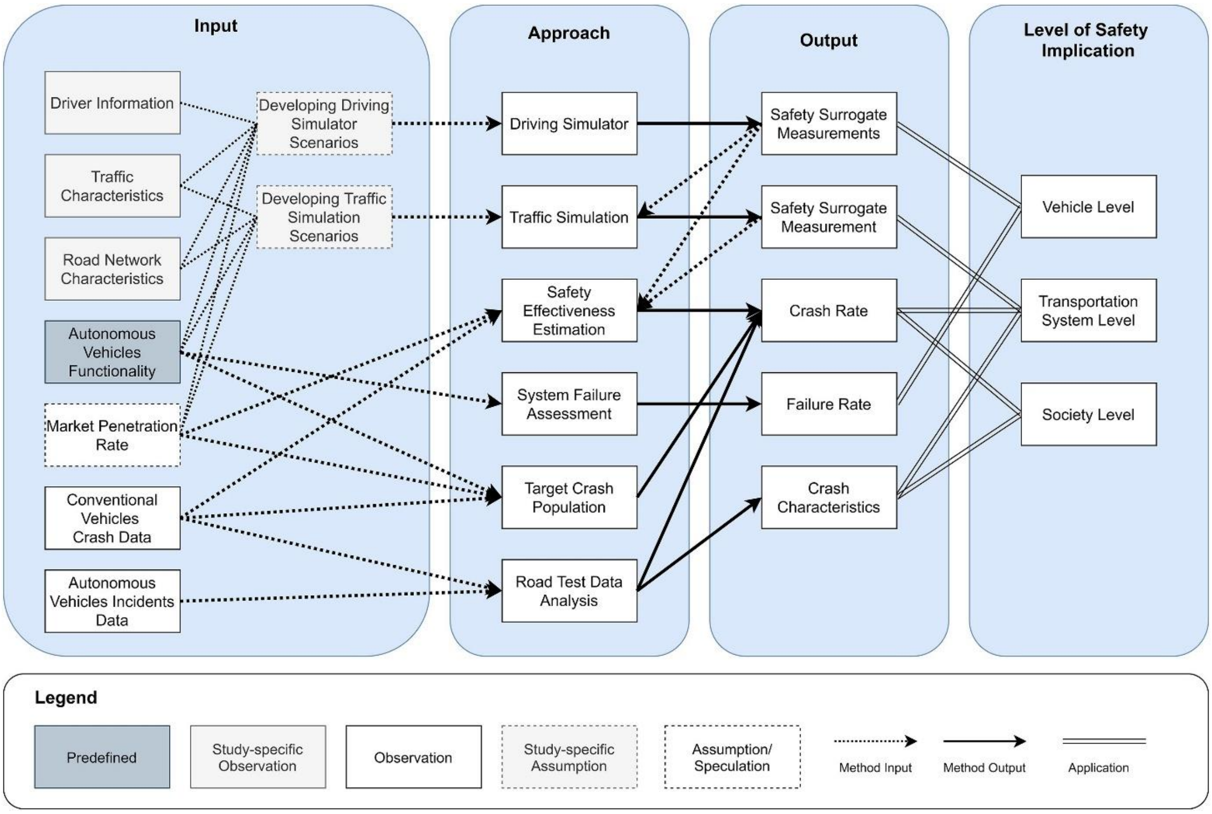

Figure 24. Inputs, outputs, and potential application of CAV safety quantification approaches [129].

3.6. KEY FINDINGS

This section contains the main findings and conclusions of the impact of automated driving at the infrastructure level that can be grouped into the following categories: (i) impact of automated driving on road classification systems, (ii) current automated driving limitations, (iii) role of connectivity in automated driving, (iv) definition of key concepts linked to automated driving, and (v) the implications of automated driving on safety.

In the last years, some efforts have been carried out to address the integration of CAVs in road classification systems [3] [17] [18] [20]. However, the proposed classification systems are based on different and diverse approaches –physical infrastructure, connectivity, and vehicle automation level– and, therefore, a harmonization is required. Most of criteria included in these systems are not linked to Key Performance Indexes, making their implementation harder. Additionally, dynamic conditions of the road –e.g., traffic volume or weather conditions– were not included in the proposed systems to determine the capability that a road has to enable an automated driving. Although policies and regulations are needed to boost the use of CAVs and consumer acceptance is crucial to increase CAV sales, the level of automation of a road should not depend on these attributes.

Although vehicle technology is constantly enhancing and evolving, the sensors and algorithms installed in CAVs cannot cope with specific challenging situations. Demanding road geometry –sharp horizontal and vertical curves and narrow lanes– usually leads to system disengagements. In addition, diverse research found that 150 mm width and 150 mcd/m2/lx retroreflectivity road markings ease CAVs operation. In this way, high-capacity roads –freeways, expressways, and motorways– are already ready to integrate CAVs as their features encourage road readability and connectivity. In addition, this road category opens up the creation of dedicated lanes (DLs).

Most TSR (Traffic Sign Recognition) systems recognize only posted speed limits and priority of way signs such as STOP, yield, etc. Nevertheless, the performance of these systems depends on the position –up to transverse distances of 10 m– and orientation –up to 45° perpendicularly to the road– of the traffic signs. Other critical aspects are the maintenance of traffic signs and the environmental lighting as the accuracy of TSR systems decreases with a poor maintenance and in situations of low or altered lightness. Furthermore, Variable Message Signs present additional limitations linked to the intrinsic aspects to this technology: (i) contrast and adaptability to surrounding light, (ii) interpretation of LEDs to form characters and pictogram, and (iii) image flickering.

Despite the few studies quantifying the influence of pavement condition on CAVs performance, it is clear that the state of the pavement surface plays a critical role in automated driving. To this regard, the new road classifications that include the particularities of these type of vehicles agree with a good pavement condition is needed to achieve the highest levels of automation.

The main environmental factors affecting CAVs performance are weather and lighting. Unfavorable weather conditions –heavy rain and fog– makes road marking and traffic sign recognition very difficult as these tasks are carried out by vision cameras that are very sensitive to visibility. Related to this, street lighting and tunnels can also influence the performance of CAVs. An improvement of street lighting, in terms of better illumination or more closely spaced lights, may be required to ensure that the visibility of road markings, signals, and signs is suitable for an effective CAVs performance. Furthermore, tunnels are linked to two important issues: (i) sudden changes in illumination conditions and (ii) low GNNS signal coverage. Although some innovation solutions have been proposed to deal with both issues, further research is needed to stablish standardized solutions and consistent with automated vehicles' capabilities.

Many car manufacturers are developing safety and communication systems to avoid collisions with non-motorized vehicles, such as pedestrians and cyclists. However, current interaction patterns and strategies cannot be automatically transferred to a situation with automated vehicles or to a situation with vehicles with different levels of automation. Above all, pedestrian and cyclist behavior are often unpredictable.

In addition to above-mentioned previous shortcomings or limitations, it should be noted that speed is a critical factor in road marking recognition because information processing must be faster as the vehicle speed increases. Related to this phenomenon, the Automated Speed was defined as the maximum speed that an automated vehicle can achieved at a specific road geometric element. Furthermore, Advanced Driver Assistance Systems are usually limited to specific range of speeds. Adaptive Cruise Control (ACC) usually works from 30 km/h, while Lane Keeping and Centering Assist (LKA and LCA) work when the vehicle speed is over 60 km/h.

Another of the most important challenges concerning automated driving is connectivity. Currently, there are two V2X communication approaches using different underlying technologies. While the IEEE's approach is DSRC (Dedicated Short-Range Communications), which supports vehicular ad-hoc connectivity WLAN technologies standardized as IEEE 802.11p – known in America as WAVE and in Europe as ITS-G5 –, the 3GPP's approach is based on LTE (Long Term Evolution), which consists of cellular technologies (C-V2X).

Roadside Units (RSUs) are using DSRC communications and need the vehicle speed be relatively low for switching. However, recent C-V2X communications based on 5G New Radio have emerged as a complementary access technology in order to provide sophisticated applications and use cases with more stringent Quality of Service (QoS) requirements –e.g., platooning or advanced driving–.

Highly automated vehicles need to monitor everything taking place on the route ahead, even beyond the range of their sensors. Connected and Automated Vehicles (CAVs) with their sophisticated sensing systems are also part of the solution, but the quality of traffic information needs to be improved. To this regard, CAVs need basically two types of information systems: (i) real-time information and (ii) rules and regulations of any restrictions ahead. Therefore, a highly versatile framework that supports several wireless technologies is needed, especially to allow high-level automation. For that purpose, a strong cooperation between all stakeholders is mandatory.

In the fourth subsection, some main concepts linked to automated driving have been presented and discussed. It is important to distinguish between the key concepts of Operational Design Domain (ODD), Operational Road Section (ORS), Level of Service of Automated Driving (LOSAD) [7], and Infrastructure Support Levels for Automated Driving (ISAD) [4].

According to the SAE J3016, an ODD refers to 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" [5]. Therefore, an Operational Design Domain can be defined as a road section that meets some characteristics that allow the driving automation system to perform. Many of these characteristics refer to the roadway type and road infrastructure, and some others refer to the environment, traffic conditions, maximum speed attainable by the driving automation system, etc. These factors also involve variable –i.e., non-static– parameters. Given the early stage of ODDs awareness and implementation by industry, it might be easier to define them by referring to the limitations, i.e., the conditions that are out the ODD.

To foster the expansion and implementation of ODDs, it is necessary to give a better, more detailed compendium of all parameters and thresholds that might intervene, i.e., a taxonomy. There have been recent efforts in that direction. A first official approach for ODD taxonomy was introduced by the British Standard Institution, which considered three main attributes: (i) scenery, (ii) environmental conditions, and (iii) dynamic elements [114]. The European ITS Platform (EU EIP) [102] developed another taxonomy, differentiating between (i) physical infrastructure, (ii) digital infrastructure, (iii) communication infrastructure, and (iv) infrastructure operations and maintenance. In 2020, the Society of Automotive Engineers (SAE) released a report with a conceptual framework of ODDs [116]. This framework focuses on the physical road infrastructure including its geometry, the environment, and the behavior of other road users. OEMs are encouraged to explicit and make public the factors supporting/limiting their ODDs. The following factors are proposed: (i) weather- and climate-related environmental conditions, (ii) surface road conditions, (iii) operational restrictions, i.e., other aspects within the operational environment not related to the first category, (iv) road users, (v) non-static obstacles on the road, and (vi) connectivity to other road users, infrastructure, and traffic management centers.

The most remarkable limitation to ODDs is that these have been defined from the point of view of the vehicle, and every single vehicle (or model) will have its unique –and time varying– ODD. Therefore, a road segment being drivable by an automated vehicle is not a property given or managed by the road authority/operator, but a varying characteristic of every single automated vehicle.

The lack of a standardized definition of ODD hinders OEMs to explicit their ODD constraints. In the end, this makes it more difficult for road administrators to be aware of which road segments are more adequate for automation.

In addition to the elements that an ODD taxonomy should include, thresholds for these elements should be applied too (e.g., minimum radius compatible with automation for a certain speed; minimum road marking width, etc.). These thresholds should be robust, i.e., they should ensure that a vehicle lying within the ODD range would not release control triggered by this factor.

Establishing clear ODDs is especially important for SAE levels 3 and 4. For lower levels, the driver is the one responsible for all the Driving Task, given the relatively frequent disengagements. SAE level 5 is the top level, a vehicle capable of driving anywhere regardless ODDs.

To facilitate the application and management of ODDs from the road infrastructure side, it is necessary to generalize the concept to a traffic stream with vehicles showing different automation capabilities. Within a certain road segment, the different vehicles will present specific ODD-compliant sections, generated by different factors. The zones that are ODD-compliant to all vehicles are indeed sections that can be driven autonomously by all vehicles. Knowing this information is very important for road authorities, since they could actively work towards increasing their length and adapting new sections.

These sections are proposed to be called “Operational Road Sections” (ORS). From a practical perspective, an ORS should be established in all zones that match with all vehicles’ driving automation systems. It should be noted that these ODDs should be robust enough to prevent disengagements if some of the dynamic factors slightly vary (i.e., ORS should be as static as possible). By making ODDs explicit, ORS would be easier identified, and OEMs could receive feedback from road administrations to improve their systems.

ORSs, like ODDs, will vary in time. At the beginning, only smooth sections at freeways are expected to be supported by all driving automation systems. As the technology evolves, other sections will become compatible with all systems, extending the ORS application. Active adaptation of road sections would accelerate this ORS generalization, but to select the most cost/effective measures, ODDs should be made explicit.

The ODD may terminate at some point, either in a planned way (the vehicle reaches an ODD physical boundary) or abruptly (some factor exits the safe zone and terminates the ODD). In both cases the vehicle might be capable of performing a Dynamic Driving Task (DDT) fallback, which is not a regular DDT but provides some capabilities to take the vehicle to a safe stop. This situation is called a “Restricted Operational Domain” (ROD).

For every single vehicle, the ODD-compliant sections along a road itinerary are expected to be discontinuous. For SAE levels 3 and 4, the driver is expected to be able to shift to a secondary task while the vehicle is in charge of the DDT. A problem arises under three circumstances: (i) the vehicle experiments a failure that stops automation abruptly, (ii) the Automated Driving System (ADS) fails, and (iii) the ODD approaches to its end, which is already known by the driving automation system. On the contrary to previous situations, the vehicle has more time to plan how to perform and warn the driver.

In all these cases, the Dynamic Driving Task has to be released to the human driver, who might be attentive to a secondary task. Hence, the ideal situation is a planned handover. Nevertheless, if the driver is unable to take over control of the vehicle, SAE level 4 and 5 ADSs can take the vehicle to a

Minimal Risk Condition (MRC), which is defined as “a condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be completed” [100]. This means that these highly automated ADSs can still control the vehicle with restricted conditions, make a decision, and take the vehicle to a position that minimizes the risk to itself and the rest of road users.

An MRC is a final state, i.e., the objective to reach by the ADS when needed. From the regular performance to the MRC, a maneuver has to be undertook (Minimal Risk Maneuver, MRM), which should also be considered to minimize the risk condition. In fact, the ADS may balance several options with diverse risk conditions, finally performing the one that presents the lowest risk in combination with the maneuvers [124].

Comparing road sections with disengagement patterns is especially relevant in order to verify to what extent the proposed ODDs are robust and match the definitions provided by OEMs. Road administrations and operators could also use this information to determine and check their ORSs –and provide newer ones–.

It is important to highlight that the driver (either human or vehicle) is the ultimate responsible for the driving task. Therefore, road administrations and operators should make explicit the available automated vehicle supporting road characteristics for every road segment and the automated vehicle will decide if it can switch on automated driving or not, according to the technologies it is equipped with.

The Level of Service for Automated Driving (LOSAD) is a concept recently introduced by García et al. [7] to indicate how ready a road segment is to host automation. Like any other Level of Service (LOS), it ranked the road segment from E –minimal automation support– to A –automation fully supported–.

Having such a direct indicator to reflect the automated-readiness level is very important for road administrations and operators. Road networks could be ranked as a function of LOSAD. Traffic volume could also be compared to it.

Another indirect way of determining the LOSAD might be through disengagement reports from marketed vehicles. By geotagging all disengagements –and, if possible, the triggering conditions–, HD maps could continuously be updated in order to indicate which road segments are more likely to disengage certain driving automation systems.

The LOSAD concept, despite still requiring further refinements upon the information that finally becomes available, is a complementary parameter to the Infrastructure Support Levels for Automated Driving (ISAD) [4]. Like LOSAD, the ISAD is categorized in five levels (A-E), being A the highest connectivity support level, to E (conventional infrastructure). LOSAD describing how vehicles’ ODDs interact with the road infrastructure, and ISAD indicating the connectivity capabilities, establish a sound basis to foresee how Connected and Automated Vehicles are likely to perform along a road network.

The implications of automated driving on safety were later presented and can be analyzed at diverse levels –(i) vehicle, (ii) transportation system, and (iii) society– and quantified by means of different approaches –(i) target crash population, (ii) road test data analysis, (ii) traffic simulations, (iii) driving simulators, (iv) system failure risk assessment, and (vi) CAV safety effectiveness–. At a vehicle level, CAVs can be examined by means of their contribution to the critical driver-related reasons for crashes, such as distractions, inattention, or performance error. At a transportation system level, a reduction in the number of traffic conflicts and crashes is expected with the integration of CAVs. At a society level, crashes are one of the main health concerns and the health impacts of CAVs can be studied by comparing crash occurrence under different Penetration Market Rates (PMR), including the scenario only with human-driven vehicles. Obviously, these safety implications depend on the automation levels of the CAVs available on the market.

According to the literature review, the current status of automation and connectivity has been found immature and therefore lacking sound business models on the participation, responsibilities, and investments of the main stakeholders: Road Administrations and Operators, OEMs and TIER1s, cellular communication operators, HD maps and traffic data providers, etc.

4. DESIGN AND ANALYSIS OF QUESTIONNAIRES

Due to the high level of uncertainty on the studied phenomenon and the numerous sectors involved in it, two questionnaires were designed to identify the main concerns and priorities of Road Administrations (RAs), Road Operators (ROs) and the automotive industry (OEMs and TIER1s).

To provide a wide perspective of the phenomenon the questionnaires were sent worldwide thanks to the collaboration in survey dissemination of PIARC. Particularly, Questionnaire 1 was sent to all National Road Administrations –including those from Low- and Middle-Income Countries (LMICs)– and Road Operators that take part of PIARC. However, Questionnaire 2 was sent to those companies of the automotive industry that previously collaborated with the UPV Team and/or supported this Special Project. Particularly, the contacted companies were Tesla, BMW, VW, Seat, Mobileye, Bosch FICOSA, and others through the Spanish Automotive and Mobility Technology Platform.

The findings of the analysis of the questionnaires complemented the conclusions of the

Literature Review and, therefore, were considered in the definition of the proposed Smart Roads Classification.

4.1. Design of questionnaires

This section presents the content of Questionnaire 1 and 2. An extended version of them can be found in Appendix A4. Questionnaires which includes the specific questions and the type of answer for each.

4.1.1. Questionnaire for Road Administrations and Operators

Questionnaire 1 aimed at identifying current worldwide road classification systems, determining the road condition at a national or regional level, and knowing the main criteria that RAs and ROs consider essential to integrate CAVs in road classification. For this, the questionnaire was divided into six sections: (i) General information, (ii) Characterization of the national/regional road network, (iii) Connectivity, (iv) Working on CAVs integration, (v) Smart Roads Classification, and (vi) General comments (Table 15).

Section	Items
General information	• Agency or Administration / road operator • Country • Continent/Region • Contact person • Position • Email
Characterization of the national/regional road network*	• Current Road classification system • Type of road users per road category • Traffic volume per road category • Maximum and most frequent speed limit per road category • Road marking characteristics
Connectivity*	• DSRC/ITS-G5 availability along main road corridors • 5G availability along main road corridors • 5G deployment plan • Roadside Unit (RSU) deployment status • Mobile Edge Computing (MEC) availability • Mobile network coverage along main highways • Use of ITS along main highways
Working on CAVs integration*	• Definition of policies on CAVs • Definition of strategies or plans on CAVs • Collaboration in international actions on CAVs • National Research Programs focused on CAVs • Agreement with associations related to CAVs • Public institutions and companies involved in CAVs integration

Smart Roads Classification (SRC)	• Importance of the factors to be considered by the SRC:
	  ○ Factors related to physical infrastructure
	  ○ Factors related to digital infrastructure
	  ○ Factors related to connectivity
	  ○ Additional factors related to automation
	  ○ Factors related to users
	  ○ Other factors.
	• Usefulness:

Section	Items
	○ Physical infrastructure. ○ Digital infrastructure. ○ Connectivity. ○ Automation.
General comments	• Suggestions, questions, or additional comments

**Only for Road Administrations*

Table 15. Content of Questionnaire 1.

Those sections related to the characterization of the national/regional road network and connectivity, that aimed at determining the readiness of a country or region to facilitate CAVs operation, were complemented with additional information from public sources and repositories such as the World Bank or the World Health Organization (Table 16). This information was only retrieved for participating countries.

Section	Items
Economic indicators	• Gross Domestic Product (GDP) • Gross Domestic Product (GDP) growth • Gross Domestic Product (GDP) per capita • Structure of the economy (% of GDP) • Population • Total primary energy supply by source • Road maintenance expenditure • Road Safety Level (deaths per 100k people)
Characterization of the national/regional road network	• Road density (km/km^2) • Road quality • Network length per road category
Connectivity	• Internet users (% of population) • Mobile network coverage (% of population) • 4G Availability • Average round trip time

Table 16. Additional information for participating countries.

4.1.2. Questionnaire for Automotive Industry

Questionnaire 2 was designed particularly for the automotive sector. To this regard, more specific questions were proposed concerning the performance of the sensors and the Advanced Driver Assistance Systems (ADAS) integrated in CAVs. This questionnaire was divided into five sections: (i) General information, (ii) Influence of the physical infrastructure on CAVs performance, (iii) Influence of digital infrastructure and connectivity on CAVs performance, (iv) Smart Roads Classification, and (v) General comments (Table 17).

The main objective of this questionnaire was to identify the extent to which infrastructure design – physical and digital– can facilitate CAVs performance and, additionally, to know which criteria the automotive industry considers essential for road classification.

Section	Items
General information	• Company • Contact person • Role in the company • Email
Influence of the physical infrastructure on CAVs performance	• Use of systems for lateral negotiation • Minimum operating speed for lateral negotiation systems • Minimum lane width for lateral negotiation systems • Specification of Active Cruise Control systems • Performance at speed limit per road category • Impact of road markings features on CAVs performance • Impact of pavement condition on CAVs performance
Influence of digital infrastructure and connectivity on CAVs performance	• Use of digital information • Reporting data • Benefits from vehicle connectivity

Smart Roads Classification (SRC)	• Importance of the factors to be considered by the SRC
	  ○ Factors related to physical infrastructure
	  ○ Factors related to digital infrastructure
	  ○ Factors related to connectivity
	  ○ Additional factors related to automation
	  ○ Factors related to users
	  ○ Other factors.
	• Usefulness
	  ○ Physical infrastructure.
	  ○ Digital infrastructure.
	  ○ Connectivity.
	  ○ Automation.

General comments	• Suggestions, questions, or additional comments

Table 17. Content of Questionnaire 2.

4.2. Analysis of questionnaires

4.2.1. Questionnaire for Road Administrations and Operators

The analysis of the responses to Questionnaire 1 was divided into the following stages:

1. Characterization of responses.
2. Analysis of the importance of the different dimensions that defines the proposed Smart Roads Classification.
3. Analysis of the importance level of the factors to be included in the Smart Roads Classification.
4. Analysis of current road classification systems.
5. Analysis of road users per road category.
6. Analysis of road markings.
7. Analysis of the current road connectivity availability in short- and medium-term plan.

1.1.1.14 4.2.1.1. Characterization of responses

A total of 66 responses –40 from Road Administrations (RAs) and 26 from Road Operators (ROs)– were obtained from Questionnaire 1 from March 24th, 2021 to May 4th, 2021 (Figure 25). This means that 60% and 40% of responses came from RAs and ROs, respectively. The participating RAs and ROs, together with the corresponding country, are listed in Table 18 and Table 19.

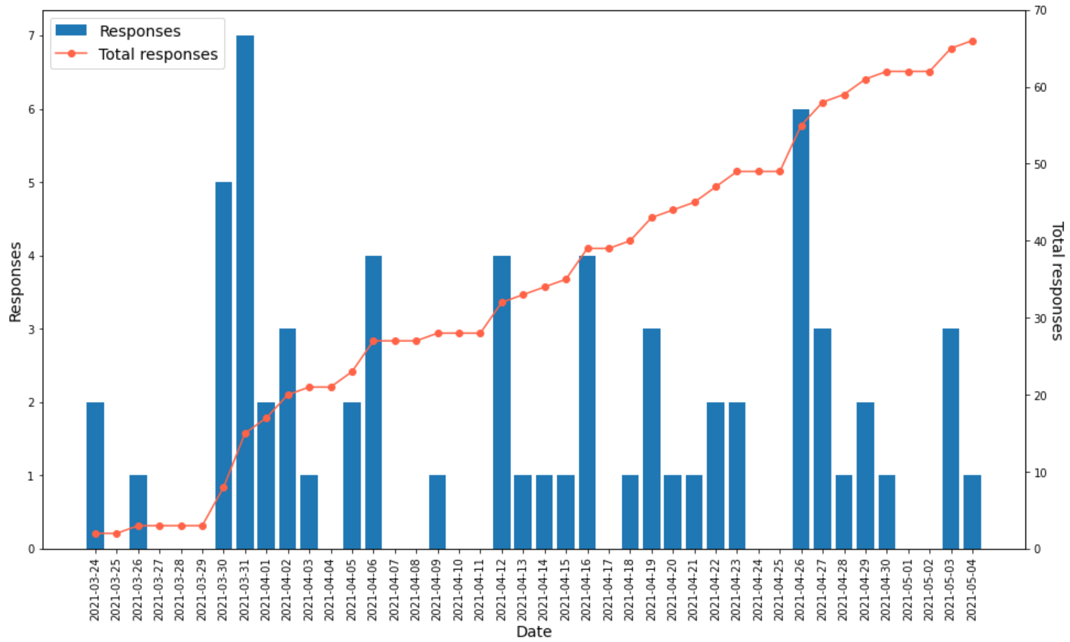

Figure 25. Number of responses to Questionnaire 1 over time.

Road Administration	Country
Departament de Mobilitat	Andorra
Main Roads WA	Australia
Department of Transport and Main Roads (Queensland)	Australia
Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology	Austria
Flemish Agency for Roads and Traffic	Belgium

Service Public de Wallonie - Mobilité et infrastructure	Belgium
Administradora boliviana de carreteras	Bolivia
Ministère des Infrastructures et du Désenclavement	Burkina Faso
Ministère des Transports du Québec, Canada (MTQ)	Canada
Dirección de Vialidad	Chile
Instituto Nacional de Vías – INVIAS	Colombia
Ministry of Transport of the Czech Republic	Czech Republic
Highways England	England
Centre for Economic Development, Transport and the Environment	Finland
Road Maintenance & Transportation Organization (RMTO)	Iran
DIATI	Italy
Vi.abilità S.r.l.	Italy
Nacional Admministration of Roads	Mozambique
Waka Kotahi NZ Transport Agency	New Zealand
Norwegian Public Roads Administration	Norway
Instituto da Mobilidade e dos Transportes I.P.	Portugal
Infraestruturas de Portugal	Portugal
Russian Road Research Institute	Russia
Государственная компания "Российские автомобильные дороги"	Russia
ФАУ "РОСДОРНИИ"	Russia
Transport Scotland	Scotland
Land Transport Authority	Singapore
Ministry of Transport and construction of the Slovak republic	Slovakia
Slovenian Infrastructure Agency	Slovenia
The South African National Roads Agency SOC Ltd (SANRAL)	South Africa
Korea Expressway Corp.	South Korea
Diputación Girona	Spain
DGT	Spain
Generalitat Valenciana	Spain
Dirección General de Carreteras del MITMA	Spain
Federal Roads Office	Switzerland
Swedish Traffic Authority	Sweden
Ministére de l'équipement, de l'habitat et de l'Infrastructure	Tunisia
Delaware Department of Transportation	United States
FHWA	United States

Table 18. Road Administrations.

Road Operator	Country
InfraTransProject Ltd.	Albania
Enseignant supérieur en route	Algeria
Groupe d'entreprises	Algeria
ASFINAG	Austria
Rocales y Concretos SAS	Colombia
CONSORCIO RUTA 40 - VIA 40 EXPRESS	Colombia
Consorcio vial helios	Colombia
Sacyr Concesiones Colombia SAS	Colombia
Femern A/S	Denmark
Vinci Autoroutes	France
Sologne ingénierie	France
Potters	France
IMEVA SPA	Italy
TECNE Spa - Autostrade per l'Italia Group	Italy
ICAPSA Y TAMU SERVICE SA	Mexico
MEXICANA DE TECNICOS EN AUTOPISTAS	Mexico
Société d'Etudes en Infrastructures - SEI-	New Caledonia
Toriola Jegede	Nigeria
Consorcio Vial Satipo	Peru
DARS d.d., Motorway Company in the Republic of Slovenia	Slovenia
N3 Toll Concession (RF) Pty Ltd	South Africa
Sacyr Concesiones International	Spain
Autovía Conquense S.A.	Spain
EMESA	Spain
Sacyr Concesiones	Spain
Abertis Autopistas España	Spain

Table 19. Road Operators.

A total of 37 countries worldwide participated in Questionnaire 1. Figure 26 indicates the number and percentage of responses per continent and Table 20 summarizes the number of responses per country, distinguishing between RAs and ROs. A georeferenced information about the responses retrieved from Questionnaire 1 can be found here.

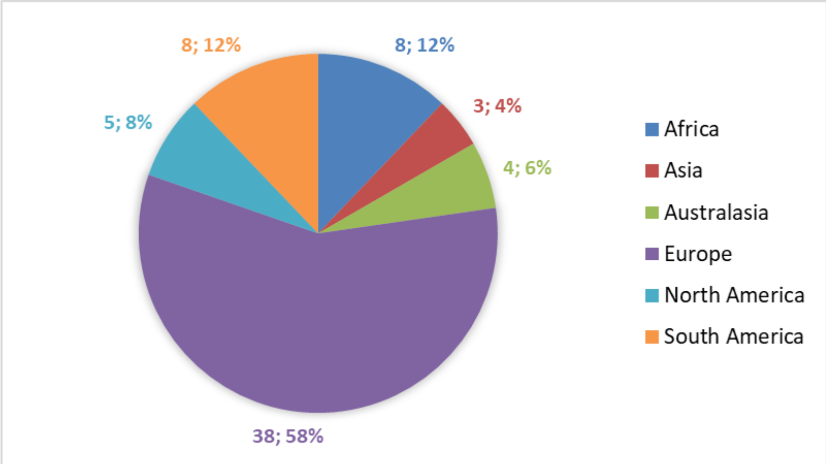

Figure 26. Number and percentage of responses to Questionnaire 1 by continent.

Country	Total Responses	Road Administrations	Road Operators	Continent
Albania	1	0	1	Europe
Algeria	2	0	2	Africa
Andorra	1	1	0	Europe
Australia	2	2	0	Australasia
Austria	2	1	1	Europe
Belgium	2	2	0	Europe
Bolivia	1	1	0	South America
Burkina Faso	1	1	0	Africa
Canada	1	1	0	North America
Chile	1	1	0	South America
Colombia	5	1	4	South America
Czech Rep.	1	1	0	Europe
Denmark	1	0	1	Europe
Finland	1	1	0	Europe
France	3	0	3	Europe
Iran	1	1	0	Asia
Italy	4	2	2	Europe
Mexico	2	0	2	North America
Mozambique	1	1	0	Africa
New Caledonia	1	0	1	Australasia
New Zealand	1	1	0	Australasia
Nigeria	1	0	1	Africa
Norway	1	1	0	Europe

Peru	1	0	1	South America
Portugal	2	2	0	Europe
Russia	3	3	0	Europe
Singapore	1	1	0	Asia
Slovakia	1	1	0	Europe
Slovenia	2	1	1	Europe
South Africa	2	1	1	Africa
Korea	1	1	0	Asia
Spain	9	4	5	Europe
Sweden	1	1	0	Europe
Switzerland	1	1	0	Europe
Tunisia	1	1	0	Africa
United Kingdom	2	2	0	Europe
United States	2	2	0	North America

Table 20. Responses to Questionnaire 1 by country.

1.1.1.15 4.2.1.2. Analysis of Smart Roads Classification section

The main objective of this Special Project was to explore a new road classification system that integrates the particularities of Connected and Automated Vehicles (CAVs). As identified in

Literature Review section, CAVs operation depends on diverse factors which can be classified in four dimensions:

i. **Physical infrastructure**, that is associated with road typology, road geometric design, pavement characteristics, road signage, and so on.
ii. **Digital infrastructure**, that refers to the availability of information for drivers and vehicles –e.g., HD maps and weather and traffic conditions– and the physical facilities that the road presents to comply with that purpose –e.g., Variable Message Signs–.
iii. **Connectivity**, that includes V2X protocols and possibilities, mobile coverage, availability of Roadside Units (RSU), and Cooperative Intelligent Transport Systems (C-ITS).
iv. **Automation**, that refers to the capacity to support automated driving.

The level of importance of each dimension was qualified by the participating RAs and ROs by means of a Likert scale, from 1 -no interested at all- to 5 -highly interested-. Table 21 presents a statistical summary of the results, distinguishing by RAs and ROs and considering all responses together. To this regard, both RAs and ROs consider “physical infrastructure” as the most important dimension and “automation” as the less important one. Particularly for RAs, the variability of the responses per dimension decreases as its mean value increases. However, this trend was not observed for ROs.

Figure 27 represents, for a specific dimension, the percentage of responses for each value of the Likert scale, placing the average value of the scale (3) at 0%. Thus, the percentages of responses associated with importance levels 4 and 5, together with half of the percentage of responses associated with importance level 3, are located on the right-hand side. In this way, the above-mentioned trend for RAs can be visually identified as the responses for “physical infrastructure” are mainly grouped into importance levels 4 and 5 –low variability–. As the mean value of a dimension decreases, the percentage of responses for importance levels 1 and 2 rises –high variability–. However, although the mean value for “connectivity” was lower than for “digital infrastructure” for ROs, the responses for the last one presented more variability than those for “connectivity” (Table 21). This is why the total percentage of responses above 0% is greater for “connectivity”.

On the whole, the dimensions ordered from the greatest to the lowest level of importance are as follows: “physical infrastructure”, “digital infrastructure”, “connectivity”, and “automation”. Moreover, the variability of the responses increases as the level of importance decreases, leading to a consensus in the inclusion of those dimensions associated with the infrastructure –physical and digital– and to a slight uncertainty about the dimensions of “connectivity” and “automation”. This might be associated with a reluctance to make substantial investments on connectivity by ROs and a lack of knowledge about automated vehicle performance in road community.

	Physical infrastructure	Digital infrastructure	Connectivity	Automation
Road Administrations				
Count	40	39	39	38
Mean	4.50	4.28	4.10	3.71
Std. Dev.	0.75	0.86	1.05	1.18
Min	2	2	2	1
25%	4	4	4	3

50%	5	4	4	4
75%	5	5	5	5
Max	5	5	5	5
Road Operators				
Count	25	25	25	25
Mean	4.64	4.08	4.04	3.84
Std. Dev.	0.76	1.04	1.02	0.85
Min	2	2	1	2
25%	5	4	4	3
50%	5	4	4	4
75%	5	5	5	4
Max	5	5	5	5
Road Administrations & Road Operators				
Count	65	64	64	63
Mean	4.55	4.20	4.08	3.76
Std. Dev.	0.75	0.93	1.03	1.06
Min	2	2	1	1
25%	4	4	4	3
50%	5	4	4	4
75%	5	5	5	5
Max	5	5	5	5

Table 21. Importance level per dimension.

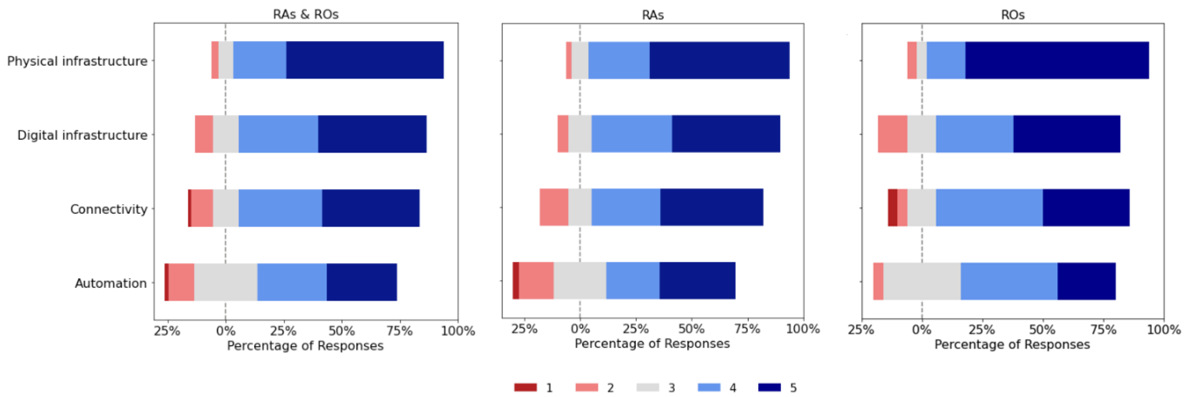

Figure 27. Importance level per dimension.

Sorting the responses by countries some particularities were observed (Table 22 and Figure 28). Both Australasia and North America consider "automation" very important as the administrations of the countries of these regions –e.g., the United States and Australia– have recently conducted research on this dimension. The region that places less importance on "connectivity" is Europe despite the great effort boosted by the European Commission in the last years. Although the number of Asian countries is low –only three– all of them consider "connectivity" as the most important dimension. Finally, both Africa and South America give more importance to those dimensions linked directly to the infrastructure –physical and digital–. This fact could be explained by the lack of experience of the countries of these regions in "connectivity" and "automation" dimensions.

	Continent	Count	Mean	Std. Desv.	Min.	25%	50%	75%	Max
Physical infrastructure	Africa	8	4.63	0.52	4	4	5	5	5
	Asia	3	4.33	0.58	4	4	4	4.5	5
	Australasia	4	4.75	0.50	4	4.75	5	5	5
	Europe	38	4.50	0.80	2	4	5	5	5
	North America	5	5.00	0.00	5	5	5	5	5
	South America	7	4.43	1.13	2	4.5	5	5	5
Digital infrastructure	Africa	8	4.38	0.52	4	4	4	5	5
	Asia	3	4.67	0.58	4	4.5	5	5	5
	Australasia	4	4.25	0.96	3	3.75	4.5	5	5
	Europe	38	4.16	1.05	2	3.25	5	5	5
	North America	4	4.50	0.58	4	4	4.5	5	5
	South America	7	3.86	0.90	2	4	4	4	5
Connectivity	Africa	8	4.38	0.92	3	3.75	5	5	5
	Asia	3	5.00	0.00	5	5	5	5	5
	Australasia	4	4.50	0.58	4	4	4.5	5	5
	Europe	38	3.84	1.10	1	3	4	5	5
	North America	4	4.75	0.50	4	4.75	5	5	5
	South America	7	4.00	1.00	2	4	4	4.5	5
Automation	Africa	8	3.63	1.06	2	3	3.5	4.25	5
	Asia	3	4.00	1.00	3	3.5	4	4.5	5
	Australasia	4	4.50	0.58	4	4	4.5	5	5
	Europe	38	3.63	1.10	1	3	4	4.75	5
	North America	4	4.50	1.00	3	4.5	5	5	5
	South America	6	3.67	1.03	2	3.25	4	4	5

Table 22. Importance level per dimension, grouped by continent.

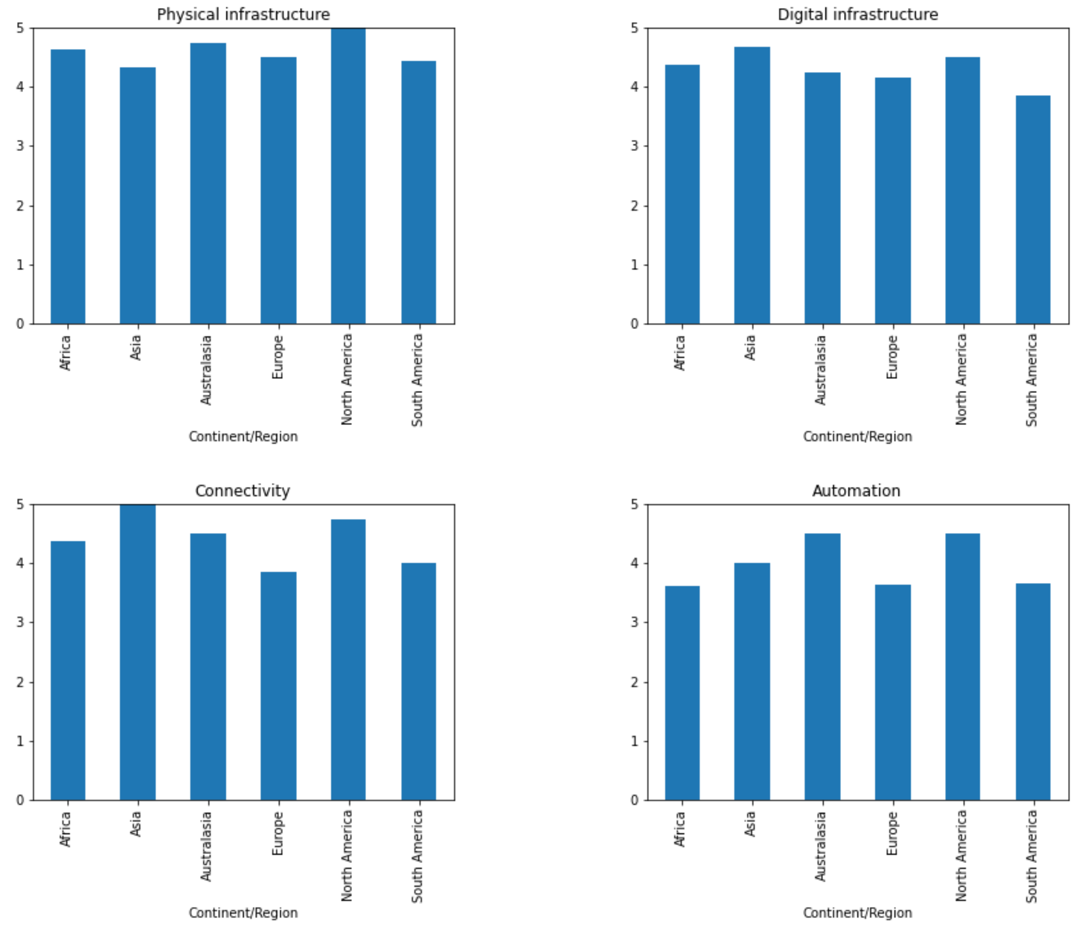

Figure 28. Importance level per dimension, grouped by continent.

1.1.1.16 4.2.1.3. Analysis of factors

The limitations of the operation of Connected and Automated Vehicles (CAVs) depend on a wide variety of factors that can be grouped mainly into the dimensions presented previously –physical infrastructure, digital infrastructure, connectivity, and automation– and an additional dimension related to road users. Particularly, Questionnaire 1 contained a section for the assessment of the level of importance of diverse factors included in each dimension.

Table 23 shows a statistical summary –mean value and standard deviation– and the percentage of responses depending on the importance level for each factor, respectively. Regarding those factors associated with “physical infrastructure” dimension, both RAs and ROs considered “road typology”, “road geometry” –including intersections and roundabouts–, and “road signage” the most influential factors on CAVs performance (Table 23). By contrast, “pavement characteristics” were not considered as important as previous factors, although a poor pavement condition might significantly influence CAVs operation.

All factors related to digital infrastructure, except weather information, presented a large percentage of responses with the highest importance level (5) (Figure 29). In fact, more than 80% of ROs gave an importance level 4 or 5 to the factors “variable message signs” and “signalized intersections”, indicating that road management plays an essential role in CAVs operation.

“V2X communications” and “cooperative ITS (C-ITS)” were considered as the main factors concerning “connectivity” dimension since both factors presented a great percentage of responses –especially from RAs– with importance level 4 and 5 (Figure 29). On the contrary, “mobile communications” –including 5G– and the deployment of “Roadside Units (RSUs)” showed a greater variability in the responses. While an important percentage of RAs did not consider the deployment of RSUs essential, some ROs did not seem to rely on mobile connectivity. Overall, most connectivity factors presented a lower importance level than those factors linked to the infrastructure as the percentage of responses associated with high importance levels (4 and 5) was lower (Table 23).

Although the responses associated with the factors included in “automation” dimension presented a higher variability, the results revealed a significant percentage of RAs and ROs –50%– that considered the “information about disengagement” crucial –importance level 5– in CAVs operation.

Finally, some factors related to road users were assessed. In general, RAs gave more importance to these factors than ROs as the average importance level were significantly greater for RAs (Table 23). The most important user-related factors were those linked to real-time warnings since more than 70% of RAs and ROs gave them the highest importance level (5) (Figure 29). By contrast, the remaining factors showed a high variability, being pedestrian counts the less important factor.

Dimension	Factor	RAs & ROs		RAs		ROs	
		mean	std	mean	std	mean	std
Physical Infrastructure	Road typology	4.35	0.98	4.28	1.09	4.46	0.81
	Road geometry	4.26	1.05	4.22	1.07	4.31	1.05
	Pavement characteristics	3.95	1.23	3.83	1.25	4.12	1.21
	Intersections and roundabouts	4.39	0.81	4.42	0.84	4.35	0.78
	Road signage	4.34	0.87	4.19	0.89	4.54	0.81
	Traffic calming devices	3.60	1.23	3.53	1.19	3.71	1.30
Digital Infrastructure	Variable message signs	4.38	1.00	4.33	1.01	4.44	1.00
	Signalized intersections	4.37	0.96	4.42	0.91	4.29	1.06
	HD Maps	4.27	1.04	4.33	0.99	4.17	1.13
	Weather information	3.90	1.07	4.00	1.10	3.77	1.03
	Traffic information	4.31	1.01	4.47	0.91	4.08	1.12
Connectivity	V2X	4.39	1.08	4.36	1.17	4.42	0.97
	5G	4.09	1.06	4.19	0.97	3.96	1.17
	Other types of mobile coverage	4.08	1.05	4.18	1.03	3.96	1.08
	RSU	3.96	1.15	3.91	1.24	4.04	1.02
	C-ITS	4.29	1.07	4.44	0.99	4.08	1.15
Automation	Information about disengagements	4.20	1.05	4.17	1.04	4.24	1.09
	Information about environmental conditions	3.95	1.14	4.03	1.14	3.85	1.16
Users	Real-time traffic volume	4.03	1.22	4.15	1.28	3.88	1.14
	Pedestrian counts	3.68	1.21	3.88	1.19	3.39	1.20
	Real-time bicycles and mopeds	4.06	1.09	4.09	1.09	4.00	1.12
	Real-time warning of stopped vehicles or queues	4.51	0.89	4.51	0.92	4.50	0.86
	Real-time warning of incidents or road works ahead	4.56	0.87	4.51	0.85	4.62	0.90
	Adaptive journey planner	4.00	1.12	4.06	1.20	3.92	1.02

	Availability of intelligent services	4.05	1.11	4.12	1.24	3.96	0.92
	Availability of advanced services	3.83	1.18	3.88	1.27	3.76	1.05

Table 23. Importance level for factors, grouped by dimension: statistical summary.

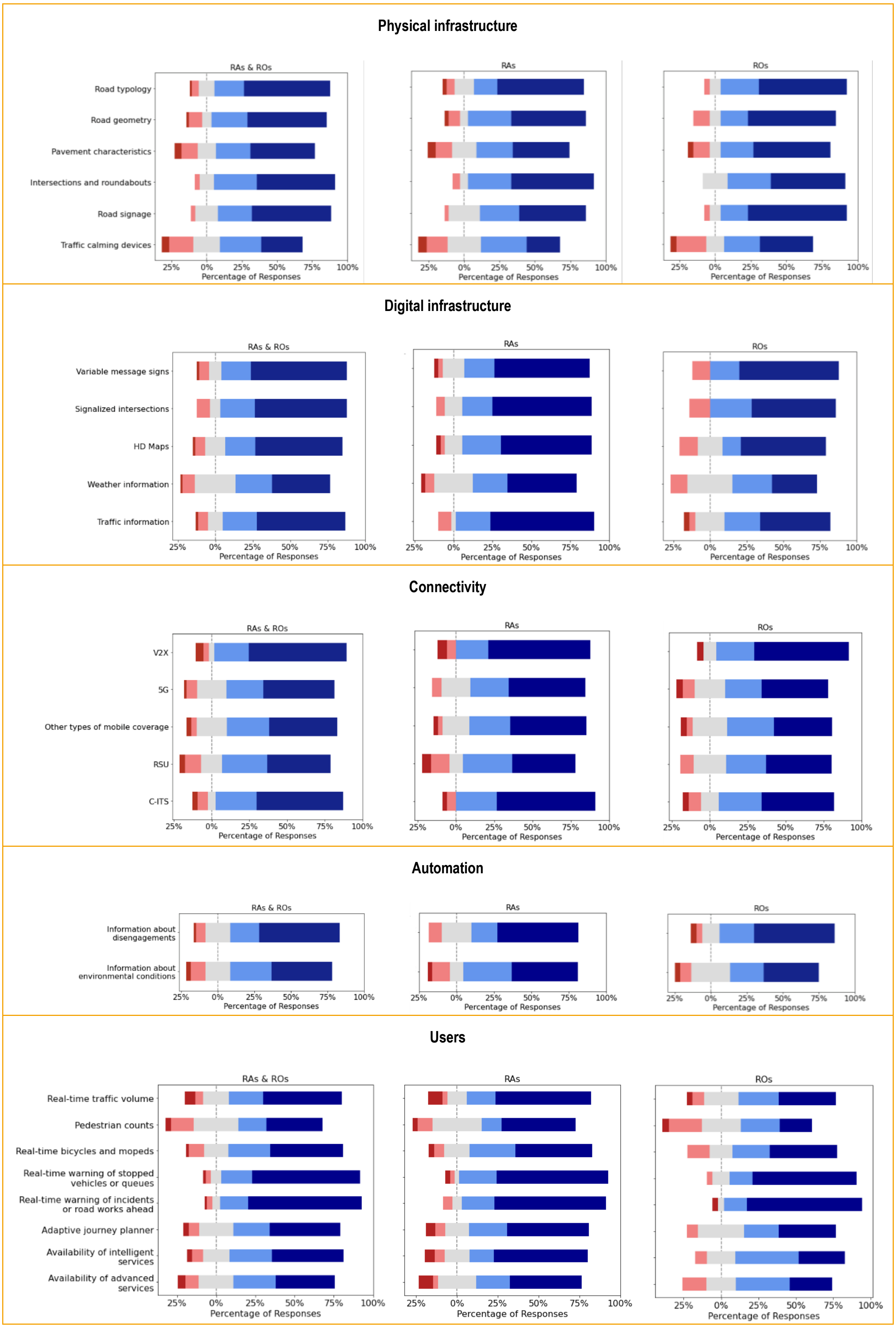

Figure 29. Importance level for factors, grouped by dimension.

1.1.1.17 4.2.1.4. Current road classification systems

When responding Questionnaire 1, RAs were asked for their current road classification system. To this regard, a list of diverse criteria was attached so that the administrations indicated which criteria are applied in their regions or countries.

Table 24 summarizes the results of the corresponding analysis. As expected, all countries currently classify their roads concerning functionality. Likewise, most of them also use the ownership and the morphology as main criteria. However, the environment is considered by approximately 70% of the participating countries, whereas the other proposed criteria –orography, users, and pavement– are only used by 54% or less of the countries.

Although the categories considered for a specific criterion differ among countries, these have certain similarity keeping the essence of each criterion. In addition to this, some countries present additional criteria due to their particularities. For instance, Norway classifies its roads in winter closed roads or night closed roads, whereas Finland divides the roads and streets into treatment categories –care classification– to prioritize the removal of snow, ice, and debris.

Country	Continent	Functionality	Ownership	Morphology	Environment	Orography	Users	Pavement
Andorra	Europe	X	X	X	X	X	X	X
Australia	Australasia	X	X	X				
Austria	Europe	X	X		X		X	
Belgium	Europe	X	X	X			X	
Bolivia	South America	X	X	X	X	X	X	X
Burkina Faso	Africa	X	X	X				X
Canada	North America	X		X	X			
Chile	South America	X	X	X	X	X		X
Colombia	South America	X				X		
Czech Republic	Europe	X	X	X				
Finland	Europe	X	X	X	X			X
Iran	Asia	X	X	X	X	X		X
Italy	Europe	X	X	X	X		X	X
Mozambique	Africa	X	X					X
New Zealand	Australasia	X	X	X	X	X	X	X
Norway	Europe	X	X	X	X	X	X	X
Portugal	Europe	X	X	X	X	X	X	
Russia	Europe	X	X	X				
Singapore	Asia	X	X	X				
Slovenia	Europe	X	X	X	X			
South Africa	Africa	X	X	X	X			
South Korea	Asia	X	X	X	X			
Spain	Europe	X	X	X	X	X	X	X
Tunisia	Africa	X	X		X	X	X	X
United Kingdom	Europe	X	X	X	X	X	X	X
United States	North America	X	X	X	X		X	X

Table 24. Current criteria for roads classification worldwide.

1.1.1.18 4.2.1.5. Road users

The analysis of road users was performed based on road category –freeway/expressway, multilane highway, two-lane rural road, crosstown road, and unpaved rural road–. To this regard, the participating countries indicated real road users per road category –not only allowed users–, which were grouped into: (i) high-speed motorized vehicles, (ii) low-speed motorized vehicles, (iii) non-motorized vehicles, and (iv) pedestrians.

Figure 30 shows, per road category, the importance of each road user in terms of percentage of participating countries indicating its presence. In this way, all countries indicated that high-speed motorized vehicles are traveling along freeways/expressways and multilane highways. However, the presence of this road user declines for two-lane rural road, crosstown road, and unpaved rural road, respectively. On the contrary, as the operating speed of the road category decreases, the presence of non-motorized vehicles and pedestrians rises.

As expected, the presence of low-speed motorized vehicles was similar to non-motorized vehicles and pedestrians on low-speed roads –crosstown road and unpaved rural road–, but on high-speed roads the presence of low-speed motorized vehicles was higher –over 25% on freeway/expressway and about 50% on multilane highway– than the previous mentioned road users. Particularly, the presence of low-speed motorized vehicles becomes important on two-lane rural roads, in which the interaction among the different type of road users is critical due to the development of medium/high speeds and the presence of mixed traffic. Although there is also an important interaction between road users on crosstown and unpaved rural roads, this is not as troublesome as on two-lane rural roads because the operating speed is lower.

Finally, it should be noted that most of countries reporting the presence of pedestrians on high-capacity roads –freeway/expressway and multilane highway– were from Africa and Australasia.

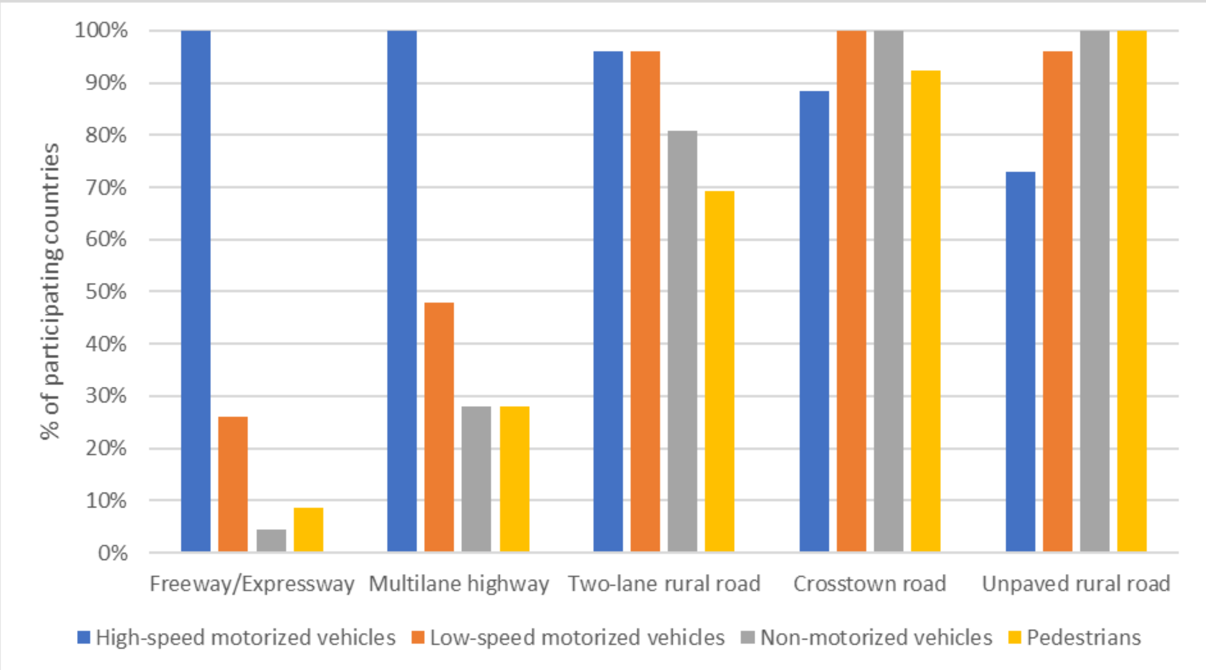

Figure 30. Road users per road category.

1.1.1.19 4.2.1.6. Road markings

Some of the most influential factors on the operation of Connected and Automated Vehicles (CAVs) are related to road markings. As identified in

Literature Review section, the success of the lateral negotiation systems (ALKS) depends on the width, condition, and configuration of the edge lines.

Figure 31 indicates, per road category, the usual width for edge lines in terms of percentage of participating countries. As expected, the width of edge lines increases with road capacity. While the common edge line width is 100 mm for two-lane rural roads, freeways/expressways usually present a 150 mm edge line width. However, there is no standard edge line width for multilane highways.

Regarding road marking condition, the participating countries reported that edge lines are mainly in good or very good condition on freeways/expressways and multilane highways (Figure 32). By contrast, one of every four participating countries reported a poor edge line condition and a third of them indicated a fair edge line condition on two-lane rural roads. This fact reveals a lack of maintenance of secondary roads that, in terms of length, are the most important roads in most of participating countries.

Finally, the configuration of the road marking was analyzed by assessing the presence or not of center and/or edge lines. Without the presence of both center and edge lines, current automated systems cannot provide an automated driving. To this regard, Figure 33 indicates how often the road contains both types of road markings –center and edge lines– per road category. While high-capacity roads almost always have center and edge lines, the presence of both lines on two-lane rural roads is not as frequent. Particularly, over 60% of participating countries reported that the presence of center and edge lines is usual on two-lane rural roads, but one every five participating countries indicated that these road markings are never or rarely painted on the pavement of this road category.

It should be noted that the country –Slovenia– reporting that no road markings are on freeways/expressways was not considered in the previous analysis.

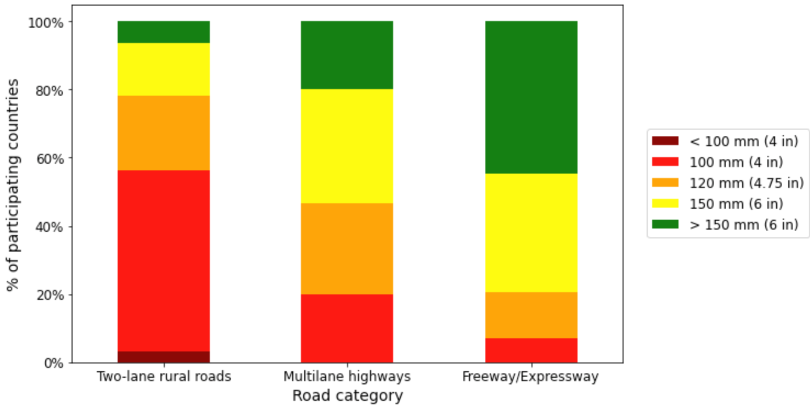

Figure 31. Edge line width in participating countries, per road category.

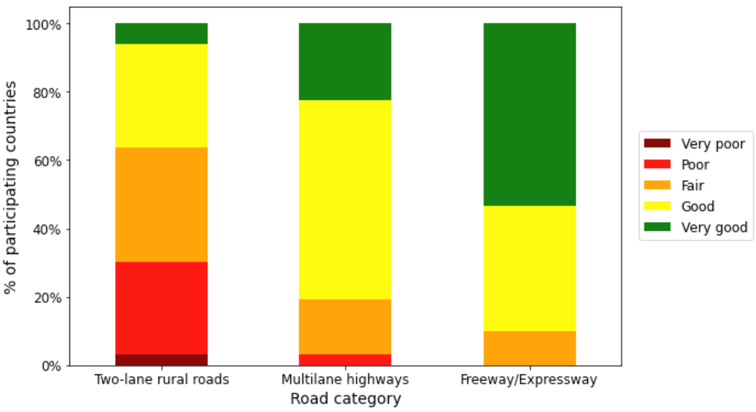

Figure 32. Edge line condition in participating countries, per road category.

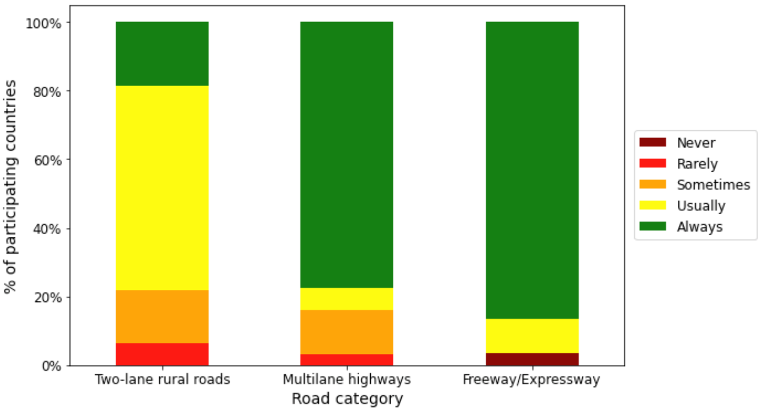

Figure 33. Presence of edge lines in participating countries, per road category.

1.1.1.20 4.2.1.7. Road connectivity

The importance of connectivity is increasing every year as vehicles with high automation levels –3 and upwards– will require to interact to "everything" to get the best out of it. However, current connectivity availability was considered poor by most participating countries (Figure 34). Despite having a good mobile network coverage along main corridors –except on African and American highways–, 5G coverage is still very low. To this regard, most participating countries pointed out that 5G technology will be available by 2025. In addition, the availability of short-range communication technology –DSRC/ITS-G5 and Roadside Units– is currently deficient to enable the highest automation levels.

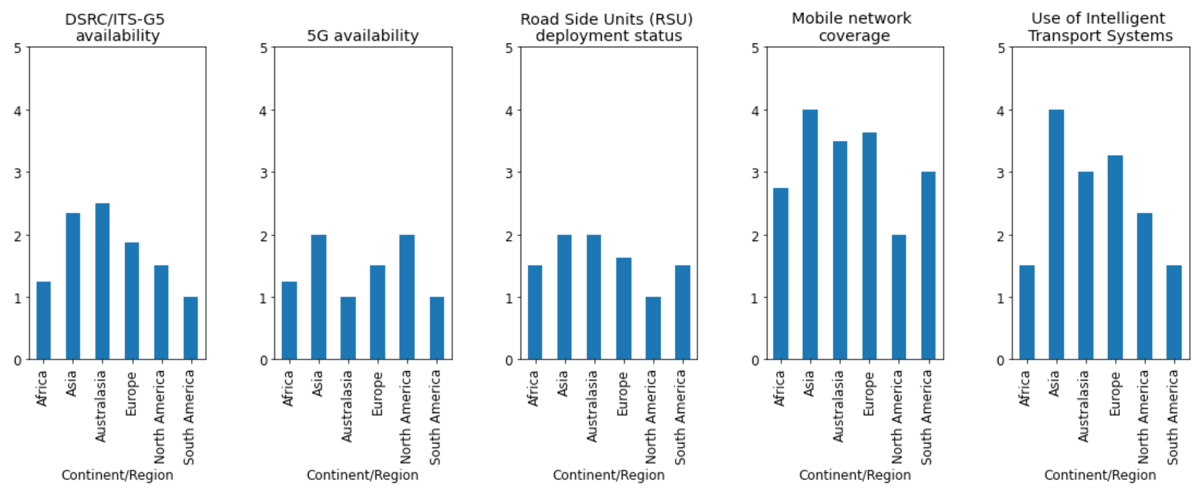

Figure 34. Current connectivity availability, per continent. Average values.

Overall, the participating countries from Africa, South America, and North America reported a low availability of communication technologies along main highways (Figure 35). On the contrary, an important percentage of participating countries from Europe and Asia considered that main highways have a good mobile network coverage and a proper use of Intelligent Transport Systems. These findings could be associated with the population distribution in the participating countries. While main highways in the participating countries from Europe and Asia –Iran, Korea, and Singapore– are connecting important cities separated by a few hundred kilometers, the distances between main cities in Africa and America might become up to several thousand kilometers. Regarding new communication technologies –DSRC/ITS-G5, 5G, and RSUs–, all continents seem to agree that their availability is currently very low.

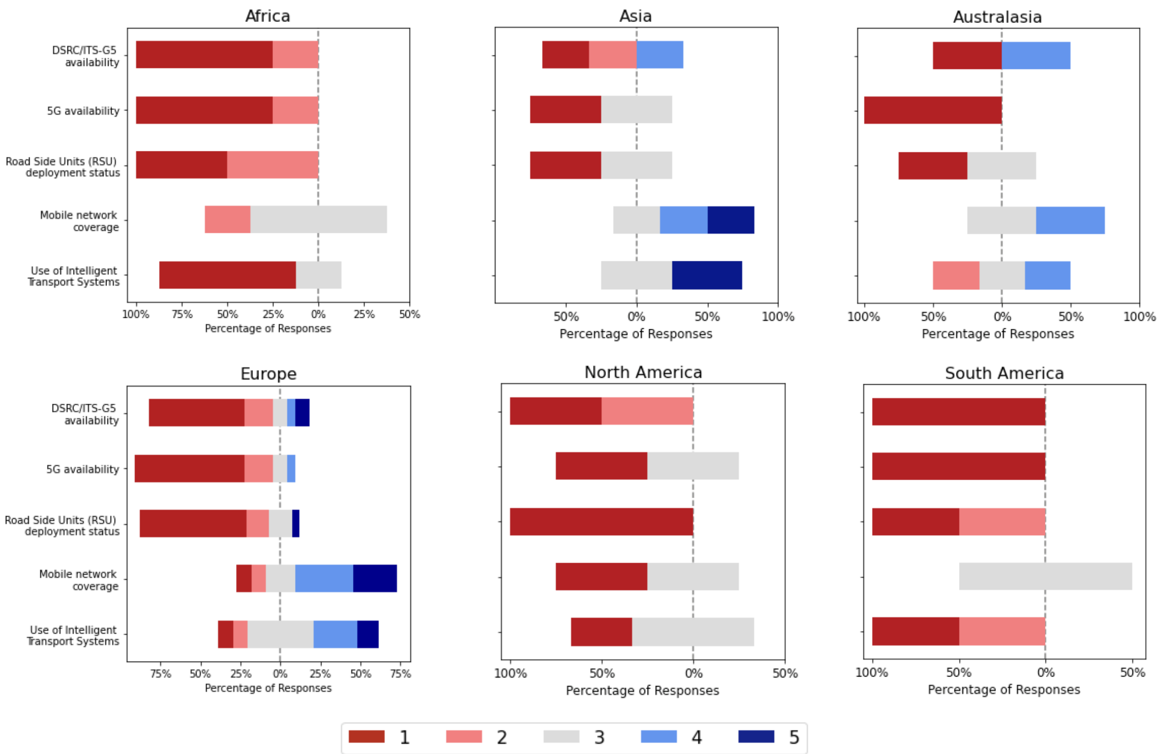

Figure 35. Current connectivity availability, per continent. Variability of responses.

4.2.2. Questionnaire for Automotive Industry

Although this questionnaire was sent to many companies in the automotive industry, there was no response. Only one of them contacted the UPV Team via email to state that they could not respond to the questionnaire because there were questions that delved into commercial or design-related information that they could not make public. Such information would be of interest to competitors and could affect investors. Therefore, in the current situation of major technological advances in automation, it is normal for companies to have concerns and reservations about their technologies and the limitations they encounter.

This means that "no answer is an answer". Developers of automated driving systems have not provided much information, so far, about the operating characteristics of the systems they are developing. Some developers have indicated that their systems need nothing from the infrastructure, even though a proper condition of the infrastructure and advances in digital infrastructure and connectivity will facilitate the higher levels of automation.

5. SRC FRAMEWORK

The Smart Roads Classification (SRC) framework aims at providing a powerful but easy-to-use tool to determine the smart level of a road segment, based on the LOSAD and ISAD indicators. Therefore, a Road Administration or Road Operator could use these classifications to rank their road networks, compare regions, plan new actions, and so on. This is called the **main classification system** and will be developed in section 5.3. 5.3. SRC Model.

However, for management purposes, the LOSAD/ISAD-based classification may not be the best option since it requires determining both indicators first. This is why all different, underlying factors related to LOSAD and ISAD have been in-depth developed in section 5.4.

These ones constitute a sort of checklist that could be used by Road Administrators and Operators to determine the smart level of their road segments. This has been named as **detailed classification system**.

It is important to highlight that both the main and the detailed classification systems correspond to the same framework, only differing in the way they are applied. Moreover, in section 5.5, some 5.5. Key Performance Indicators (KPIs) have been proposed to assess the evolution of the SRC application along time.

In order to achieve a more elaborated SRC proposal, as detailed in sections 5.3 to 5.5, a first draft of the SRC proposal was developed and served as the basis for an international survey (Questionnaire 3). The following sections describe the process carried out to derive the final SRC proposal from the first draft is described. This includes the design and analysis of the questionnaire.

5.1. DEVELOPMENT OF THE SRC DRAFT PROPOSAL

A first draft of an SRC Proposal was developed to be assessed through a general questionnaire (Questionnaire 3) to collect feedback from all worldwide stakeholders on: (i) the approach of the SRC, (ii) the identification of SRC challenges and opportunities, and (iii) the assessment of the criteria and principles used to develop the draft SRC.

To facilitate the response to the questionnaire, the following documents were made available to respondents: (i) Executive Summary, and (ii) Extended document. Although the extended document was only available in English, the executive summary was also edited in Spanish and French to accompany the survey in the three corresponding languages. The English versions of both documents are included in Appendix APPENDICES

A1. SRC Draft Proposal.

The extended document was elaborated with three sections:

I. An introduction to SRC, including the background and the proposed objectives.
II. A summary of the literature review.
III. The SRC proposal, with the characteristics of the five Smart Road Levels and the main indicators to designate them (LOSAD and ISAD), and all the different factors to be able to proceed with the classification; finally, some Key Performance Indicators are proposed to compare the status of a road network, as the SRC is implemented, both longitudinally (i.e., in time) and to the road networks of other countries or regions.

Moreover, a brief executive summary, only five pages long, was edited to facilitate the understanding of the SRC proposal without the need to spend a lot of time before answering the questionnaire.

5.2. General Survey

A third questionnaire (Questionnaire 3) was developed to assess the preliminary version of the SRC. Questionnaire 3 were sent worldwide thanks to the collaboration in survey dissemination of PIARC. All stakeholders involved and interested in the project –included those participants in Questionnaire 1 and 2 and other stakeholders with Letter of Intent– were also consulted.

In addition to this questionnaire, two webinars were developed to disseminate the draft SRC proposal. The first one was held in Madrid (Spain) on June 2nd, 2021 within the activities of Committee CT4 "Planning, Design, and Traffic" of the Spanish National Committee of PIARC, from its Working Group 3 on "New Technologies". The second webinar was organized by PIARC and held virtually on June 15th, 2021.

Below, the main findings of Questionnaire 3 are presented and, afterwards, an analysis is shown by comparing the main figures of the questionnaire with those obtained during the webinars.

5.2.1. Design of questionnaire

This section presents the content of Questionnaire 3, being an extended version of it in Appendix A4.3 Questionnaire 3 which includes the specific questions and the type of answer for each.

This questionnaire was divided into four sections: (i) General information, (ii) Application and management of the SRC, (iii) Criteria and principles of the draft SRC, and (iv) General comments (Table 25).

The main objective of this questionnaire was to collect feedback from all worldwide stakeholders on:

- Approach of the SRC. Identification of challenges and opportunities of the SRC.
- Assessment of the criteria and principles used to develop the draft SRC.

IN ORDER TO ANSWER THE QUESTIONNAIRE, THE DRAFT SRC PROPOSAL WAS AVAILABLE TO THE RESPONDENTS THROUGH THE FOLLOWING DOCUMENTS: (I) EXECUTIVE SUMMARY AND (II) EXTENDED DOCUMENT (SEE APPENDIX APPENDICES

A1. SRC Draft Proposal).

Section	Items
General information	• Type of stakeholder • Name of stakeholder • Country • Contac person • Position • Email
Application and management of the SRC	• Necessity of the SRC for the deployment of CAVs • Collaboration with the automotive industry • Communication with road users • Sharing information from the infrastructure

	• Responsibility for establishing and updating the SRLs • Responsibility for using the SRLs • Priorities to reach higher SRLs • Benefits and opportunities • Challenges and barriers • Level of understanding of the SRC proposal • Deployment of the SRC system • Level of applicability of the SRC system • Level of detail of the SRC system • Agreement with SRC objectives • Agreement with proposed KPIs • Application of the SRC at the planning and investment stage • Application of the SRC at the management stage
Criteria and principles of the draft SRC	• Relationship with current road typology classification system • Relationship with current road functional classification system • Expected SRLs in the near future • Necessity to make ODDs explicit • Necessity to report disengagements • Agreement with the number of SRLs • Agreement with the indicators –LOSAD and ISAD– considered in the SRC • Agreement with LOSAD factors • Agreement with ISAD factors
General comments	• Suggestions, questions, or additional comments

Table 25. Content of Questionnaire 3.

5.2.2. Analysis of questionnaire

The analysis of the responses to Questionnaire 3 was divided into the following stages:

1. Characterization of responses.
2. Analysis of global aspects of the proposed Smart Roads Classification.
3. Analysis of the criteria and factors included in the Smart Roads Classification.
4. Analysis of the proposed Smart Road Levels and their relationship with current road classification systems in the near future.
5. Analysis of the relationship of the automotive industry and the Smart Roads Classification.

1.1.1.21 5.2.2.1. Characterization of responses

A total of 65 responses worldwide were obtained from Questionnaire 3 from May 28th, 2021 to June 28th, 2021 (Figure 36). Despite the steady pace of responses, a peak was observed on June 4th as a result of the webinar held in Madrid (Spain) two days before.

Most of the respondents were from Road Administrations (17) and Academia (13), accounting for almost half of the responses. Road Operators and Road consulting firms were also highly represented with 15% and 12% of the responses, respectively. In this way, **40% of the respondents were from Road Administrations and Road Operators**. By contrast, **only one respondent was from the automotive industry** (Figure 37). These results reveal that the automotive industry most likely considers that the infrastructure is not playing a key role in the deployment of connected and automated mobility on current roads. More details on the role of this stakeholder in this issue is provided in 1.1.1.25. 5.2.2.5. Automotive industry & SRC.

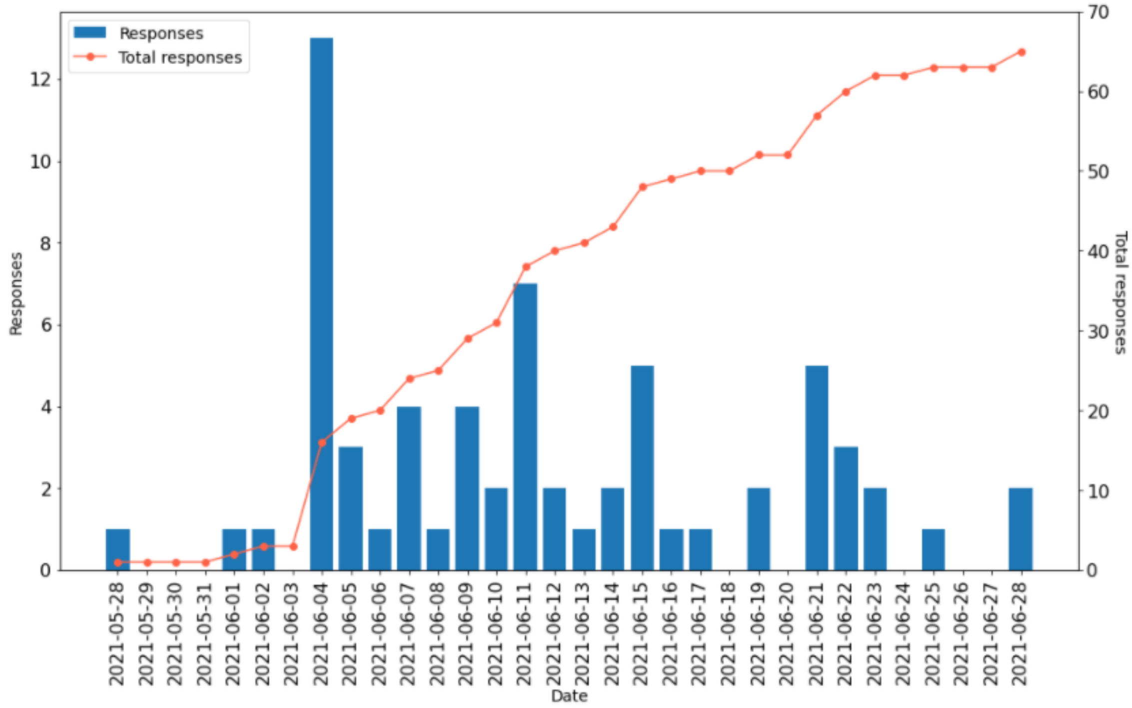

Figure 36. Number of responses to Questionnaire 3 over time.

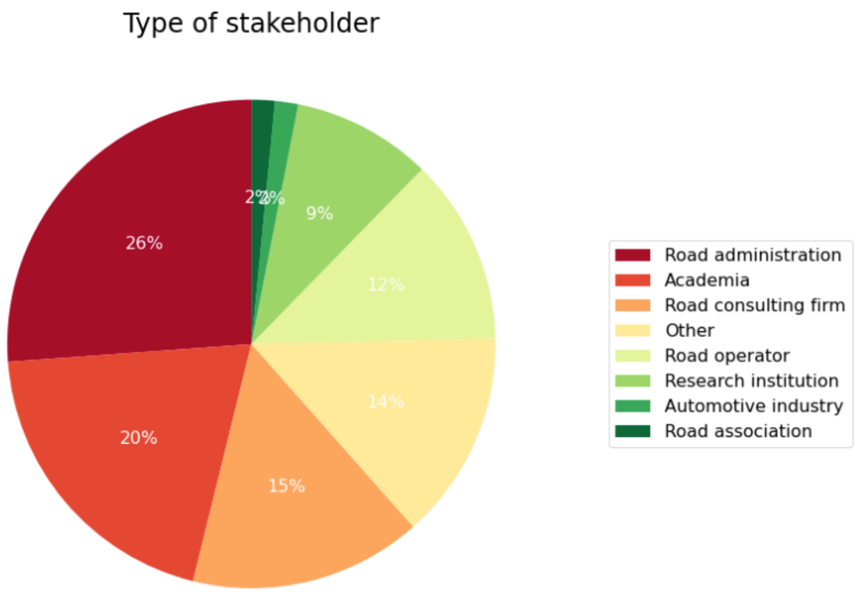

Figure 37. Percentage of responses to Questionnaire 3 by stakeholder.

A total of 33 countries worldwide participated in Questionnaire 3. Figure 38 indicates the percentage of responses per continent and Table 26 summarizes the number of responses per country. To this regard, more than half of responses came from Europe (37), while a quarter were retrieved from America (16). The over-representation of European responses could be due to the webinar held in Madrid as 12 responses (17% of total responses) came from Spain. A georeferenced information about the responses retrieved from Questionnaire 3 can be found here.

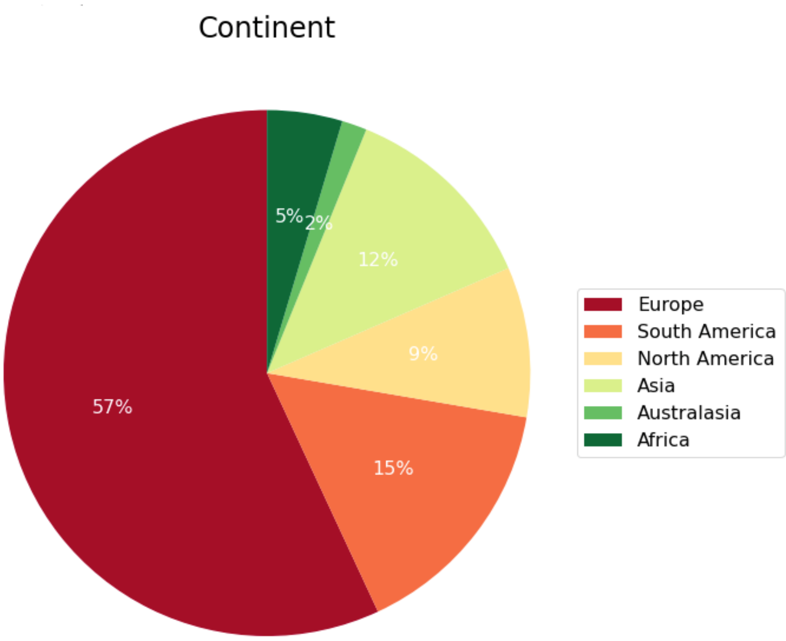

Figure 38. Percentage of responses to Questionnaire 3 by continent.

Country	Responses	Continent
Algeria	1	Africa
Argentina	1	South America
Australia	1	Australasia
Austria	2	Europe
Belgium	2	Europe
Brazil	1	South America
Canada	2	North America
Chile	1	South America
Colombia	3	South America
Côte d'Ivoire	1	Africa
Ecuador	1	South America
Finland	1	Europe
France	5	Europe
Greece	2	Europe
India	3	Asia
Italy	4	Europe
Japan	1	Asia
Malaysia	1	Asia
Mexico	1	North America

Country	Responses	Continent
Nepal	1	Asia
Peru	1	South America
Portugal	1	Europe
Russia	1	Europe
Singapore	1	Asia
South Africa	1	Africa
Korea	1	Asia
Spain	12	Europe
Sweden	1	Europe
Switzerland	1	Europe
United Kingdom	2	Europe
United States	3	North America
Uruguay	1	South America
Venezuela	1	South America

Table 26. Responses to Questionnaire 3 by country.

Finally, it should be highlighted that a total of **686 comments or suggestions were gathered** from the different open-ended questions included in Questionnaire 3. In general, over half of the respondents wrote between 100 and 250 words throughout the survey, being the average number of words used by respondents 206. More specifically, Table 27 shows the number of responses, the average and the median of the number of used words, and the number of responses using more than 25 words for each open-ended question. The average number of words per comment was 19 words.

Those questions included in "Application and management of the SRC" section associated with general aspects of the proposal (orange-shaded) gathered the higher number of responses (>85% of respondents). The rest of the questions in this section also got a high level of responses, exceeding 50% in most cases. On the contrary, the questions included in "Criteria and principles of the draft SRC" section presented a low rate of responses –from 10% to 43% of respondents–. Last but not least, approximately 50% of respondents added final comments and suggestions, being one of the most important responses in terms of number of words.

Section	Topic of the question	Count	Mean	Median	>= 25 words
Application and management of the SRC	Necessity of the SRC for the deployment of CAVs	60	27.83	22	27
	Collaboration with the automotive industry	58	19.17	14	13
	Communication with road users	56	17.75	13	14

Section	Topic of the question	Count	Mean	Median	>= 25 words
	Priorities to reach higher SRLs	60	13.02	8	10
	Benefits and opportunities	59	14.05	12	7
	Challenges and barriers	59	21.42	14	14
	Proposed objectives	41	20.10	14	14
	Other objectives	32	14.09	13	5
	Proposed KPIs	33	20.03	17	11
	Other KPIs	22	14.32	11.5	4
	Application at planning and investment stage	34	19.18	15	7
	Application at management stage	29	19.41	14	7
Criteria and principles of the draft SRC	Necessity to make ODDs explicit	28	14.68	12.5	4
	Necessity to report disengagements	4	11.50	10	0
	Number of SRLs	7	27.57	21	3
	Indicators - LOSAD & ISAD	7	32.14	18	2
	Proposed LOSAD factors	16	14.69	14	3
	Other LOSAD factors	18	8.56	5.5	1
	Proposed ISAD factors	18	22.56	17	5
	Other ISAD factors	12	9.83	10	0
General comments	Final comments	33	44.48	20	16

Table 27. Features of open-ended questions.

1.1.1.22 5.2.2.2. Global aspects

First of all, it should be noted that **four out of five respondents consider necessary the definition of a new road classification system that integrates the particularities of Connected and Automated Vehicles** (CAVs) to encourage and boost their deployment. However, Road Administrations and Operators expressed a slightly lower need (72%).

Specifically, most respondents highlight that the system is needed to ensure road safety and provide information to road users. To do this, the respondents' comments reveal that the joint work of all stakeholders is necessary to achieve a standard and universally accepted system. Some comments supporting the benefits of an SRC are below:

“This will complement the safety elements of the CAVs and with more data collected over the years can assist in proving the safety on our roads.”

“Autonomous systems need data input (from digital and physical infrastructure) to navigate safely along the roads (the physical infrastructure).”

“It's necessary a common language and a common standardization for CAV and for road environment.”

However, a few respondents indicated that the system would be very useful for all stakeholders, but not needed. In this context, the automotive industry believes that the infrastructure support is not essential for CAVs operation.

“Recent discussions with OEMs (CAV manufacturers) indicate that infrastructure support is not essential or obligatory when facilitating automated driving.”

“Although Smart Roads Classification is not necessary, it is potentially very useful. It should help auto industry and road administration be more specific when defining ODDs and CAV-related standards.”

The proposed SRC was developed based on twelve objectives. Although most of respondents agreed with all the proposed objectives, an important disagreement was identified concerning that objective associated with liability. **More than 50% of respondents considers that Road Administrations and Road Operators should not be exempt from liability** (Figure 39). To this regard, some respondents indicated that a minimum responsibility per stakeholder should be defined. Particularly, Road Administrations and Operators showed a higher level of agreement than the rest of stakeholders regarding this objective, but the percentage of disagreement was still significantly high (>35%).

Indeed, both **Road Administrations and Road Operators were considered to be the agent responsible for stablishing and updating the Smart Road Levels** of the road network (Figure 40). However, **road users, followed by automated vehicles, were considered to be the most responsible stakeholders for using the information associated with the Smart Road Level** of a road segment (Figure 41). In this case, Road Administrations and Road Operators were selected by less than one third of the respondents.

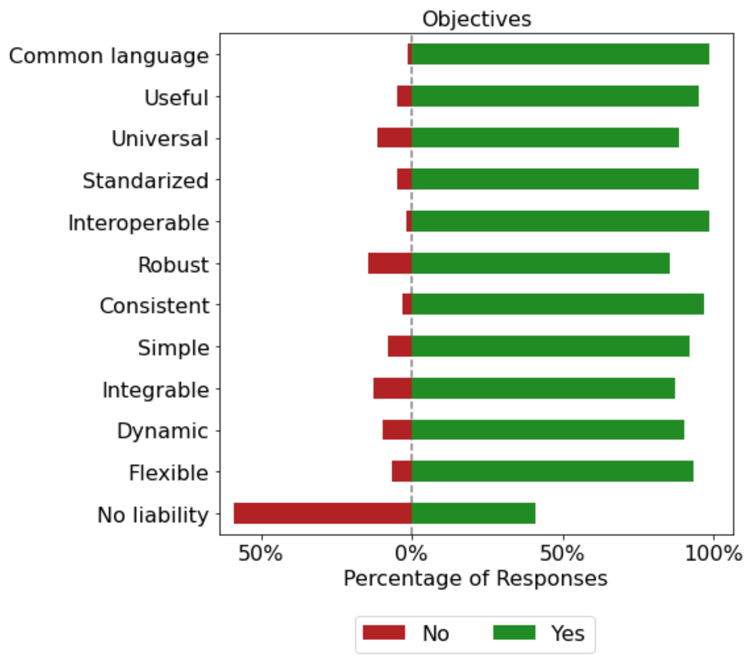

Figure 39. Agreement with proposed objectives.

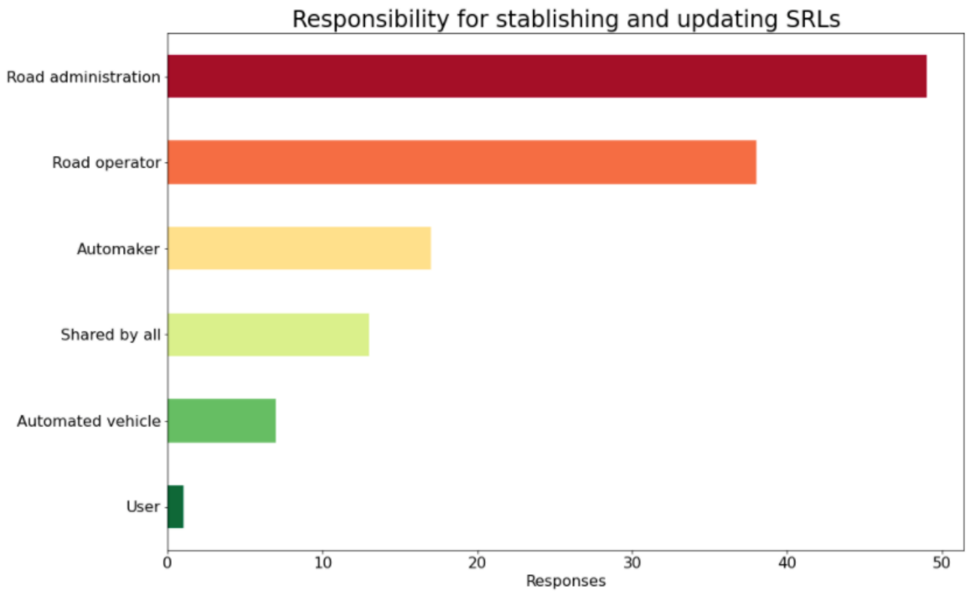

Figure 40. Responsibility for stablishing and updating SRLs.

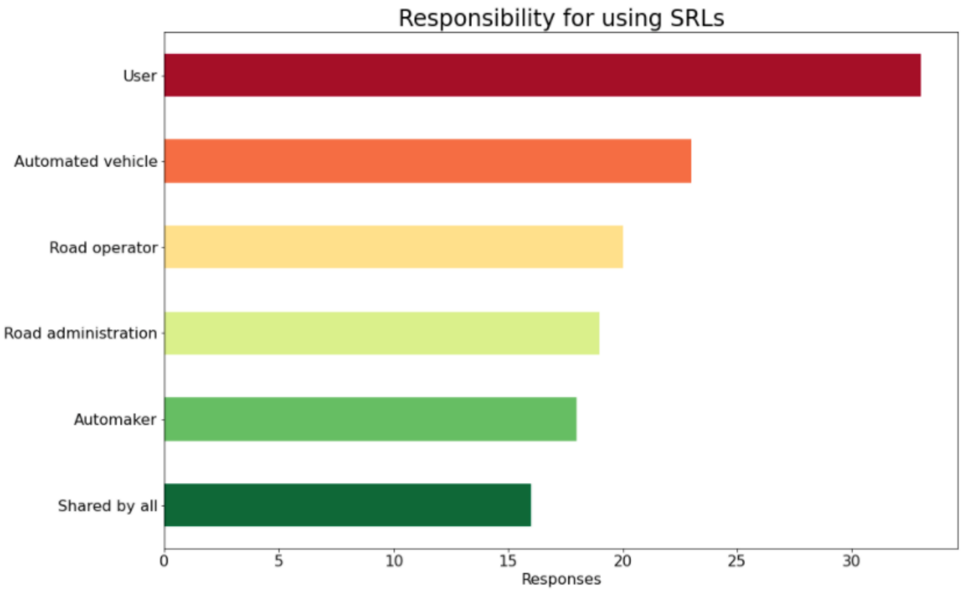

Figure 41. Responsibility for using SRLs.

In addition to the proposed objectives, **the respondents suggested the inclusion of** the following ones: (i) **safe**, to enhance road safety by providing detailed information to road users and CAVs, (ii) **operational**, to improve traffic operation, (iii) **sustainable**, to encourage the reduction of vehicle emissions, (iv) **measurable**, to clearly define metrics for each Smart Road Level, (v) **credible**, to generate confidence in road users, and (vi) **compatible with human-driven vehicles**. Below, some comments retrieved in Questionnaire 3 related to these objectives are presented:

"Safe, the system must ensure safety. Credible, to generate confidence in the user."

"This classification would also be useful for human drivers."

"Measurable, to define clearly the metrics used to define the SRL for each specific ODD."

Other general questions included in Questionnaire 3 were those related to the level of understanding of the proposal, the possibility to deploy the SRC in the near future, the applicability of the system, and the level of detail of the proposal. All these aspects were assessed considering a Likert scale from 1 –lowest, totally disagree, rarely used or insufficiently detailed– to 5 –highest, totally agree, widely used or very detailed–. Figure 42 represents, for a specific aspect, the percentage of responses for each value of the Likert scale, placing the average value of the scale (3) at 0%. Thus, the percentages of responses associated with importance levels 4 and 5, together with half of the percentage of responses associated with importance level 3, are located on the right-hand side.

As a result, the level of understanding of the proposal can be defined as medium-high since its mean value was 3.6, being considered by over 50% of respondents as high (4) or very high (5). Likewise, most of the respondents (>80%) would like the system to be deployed in the near future. Regarding the applicability of the SRC, the most selected value –the mode– was 3 (37%), meaning that the use of the system is currently limited. Finally, one third of the respondents assessed the level of detail of the proposal as fair (3), whereas 40% of them indicated a high level of detail (4). Thus, it can be said that **the proposed SRC is sufficiently detailed to be a first exploration of a new framework for the classification of the road infrastructure**.

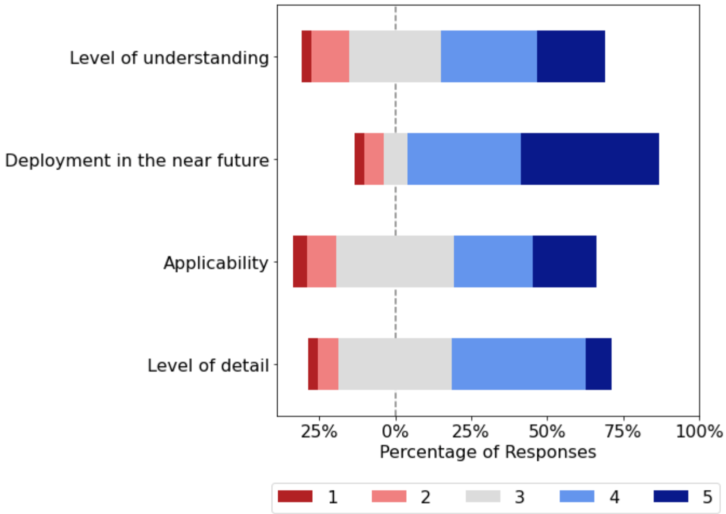

Figure 42. General questions about the proposed SRC.

1.1.1.23 5.2.2.3. Criteria and factors

After analyzing the global perception of the respondents, this section focuses on those concepts, factors, and Key Performance Indicators (KPIs) proposed for the definition of the draft of the new system.

The SRC has been defined based on two indicators of autonomous performance and connectivity support: Level Of Service for Automated Driving (LOSAD) and Infrastructure Support Levels for Automated Driving (ISAD). To this regard, it is important to note that **85% of respondents (86% of RAs and ROs) consider these indicators –LOSAD and ISAD– to be adequate for the definition of the new road classification system**. Additionally, Questionnaire 3 also included some questions concerning the importance of each LOSAD and ISAD factor (Figure 43 and Figure 44). Most of the respondents, including RAs and ROs, agreed with the different factors associated with LOSAD (>85%) and ISAD (>80%). Those ISAD factors with lower levels of acceptance were “Microscopic dynamic driving guidance”, “AV throughput”, and “Sensors for trajectories of vehicles and users”. These results might be associated with the complexity of these factors. Moreover, the respondents suggested the inclusion of “lighting condition” as a LOSAD factor and the range of C-V2X communication based on 5G as a ISAD factor.

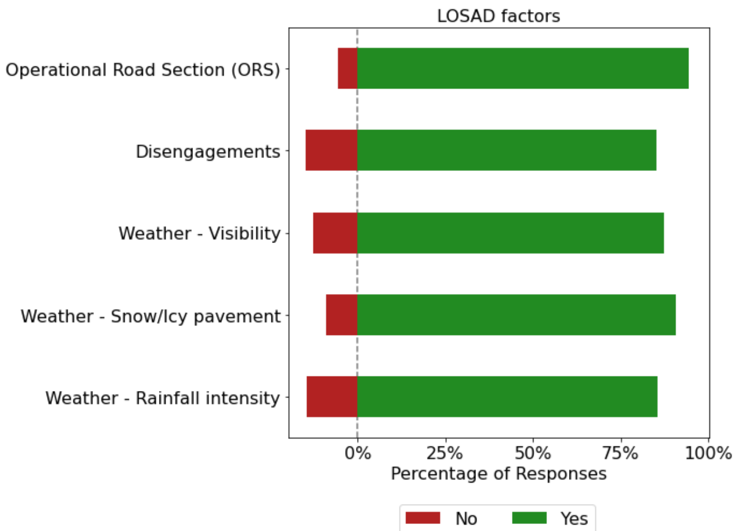

Figure 43. Analysis of LOSAD factors.

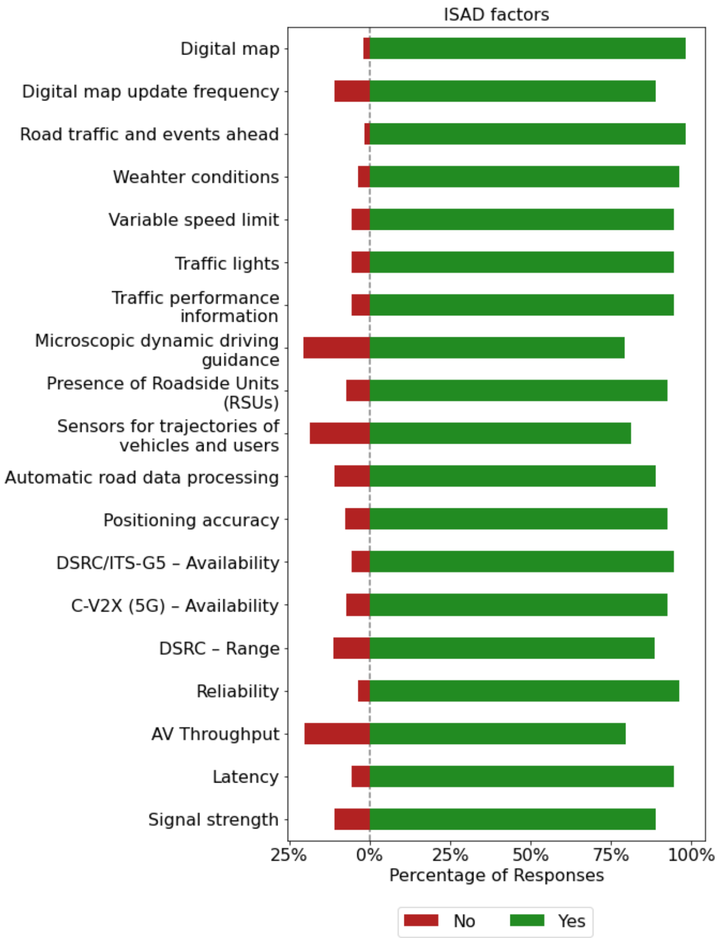

Figure 44. Analysis of ISAD factors.

Finally, the level of agreement regarding the diverse Key Performance Indicators (KPIs) was determined (Figure 45). These indicators are proposed to be used by Road Administrations and Operators so as to know the performance situation of their road network and make strategic decisions, maximizing the outcome of their investments. Overall, all proposed KPIs were considered important as at least four out of five respondents agreed with them. Moreover, according to the respondents' comments, the following KPIs should be added: (i) Average distance driven (km or mi.) without disengagement per road segments of each smart road level (replacing the previous one), (ii) ratio of average CAVs Crash Rate to all Vehicles Crash Rate, for the entire road network, and (iii) Average Travel Time Index of each Smart Road Level per road for the entire motorway-freeway-expressway network. As suggested by the participants, some KPIs previously referred to each road type category were redefined to be estimated only considering the high-capacity road network (motorway, freeway, and expressway).

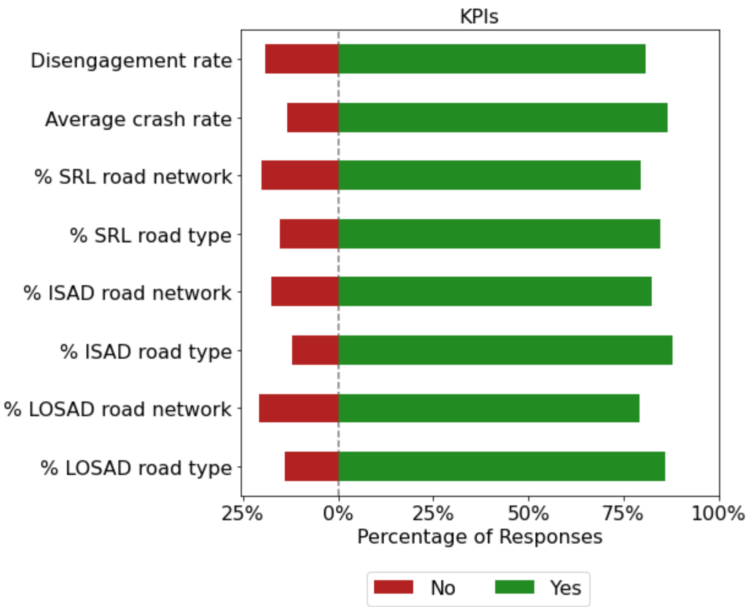

Figure 45. Analysis of KPIs.

1.1.1.24 5.2.2.4. Smart Road Levels in the near future (approx. 2030)

The main goal of the SRC is the determination of the Smart Road Level (SRL) of each road section included in a road network. Based on the possible combinations of the different LOSAD and ISAD levels, a total of five SRLs were proposed: Humanway (HU), Assistedway (AS), Automatedway (AT), Full Automatedway (FA), and Autonomousway (AU). These levels were accepted by 86% of the respondents.

Moreover, Questionnaire 3 included some items focused on the relationship between the SRC and the current road classification systems in the near future (approx. 2030). Figure 46 shows the relationship of the SRC with current road typology. As expected, high-capacity roads are expected to reach higher SRLs. Specifically, about 40% of the respondents matched “Motorway” with “Autonomousway” level. On the contrary, two-lane rural roads were associated with the lowest smart levels, with HU accounting for 44% of the responses.

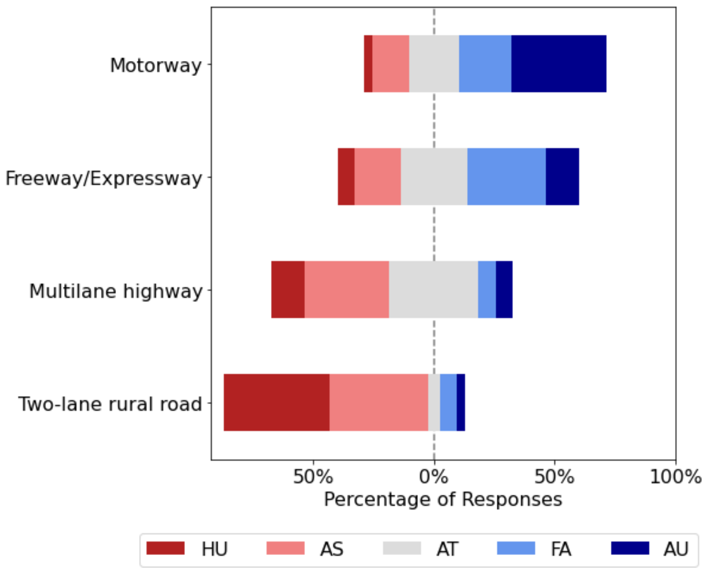

Figure 46. Relationship between SRC and road typology in the near future.

Similar findings were found when analyzing the relationship between the SRC with road functionality. The expected smart level decreases as the functionality of the road does. In this case, more than half of the respondents assigned a HU smart level to local roads. Both arterials and collectors reported an important number of responses associated with the lowest smart levels –HU and AS–, whereas only freeways resulted in a smart level higher than the medium level –AT–, with more than 30% of respondents expecting this type of roads to reach the highest smart level –AU–.

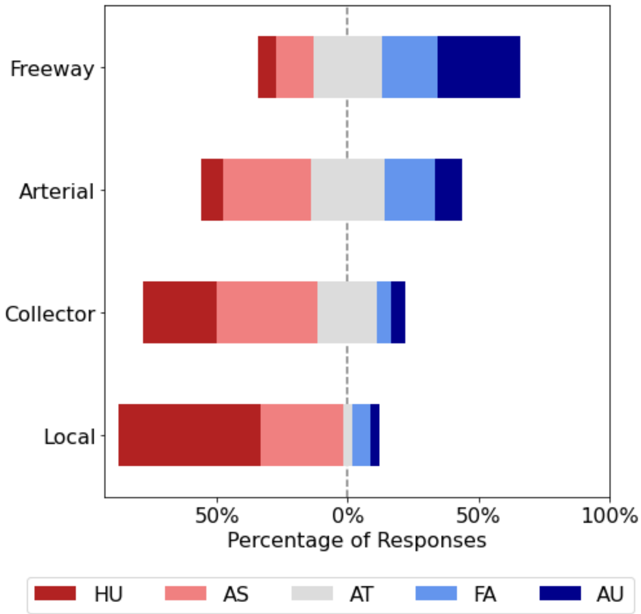

Figure 47. Relationship between SRC and road functionality in the near future.

Additionally, the respondents were asked for the expected percentage of every SRL for all the road network in their countries in the near future. In general, the lowest SRL –HU– is expected to be the most extended level as more than half of the respondents assigned it percentages larger than 60%. The response "0%" increased with the smart level so that over one out of three respondents thinks that no AU road segments will exist in the near future. Likewise, the response "1-20%" was the most selected for AT and FA levels which might be linked to the lack of confidence that stakeholders show in the role of the road infrastructure in the integration of CAVs.

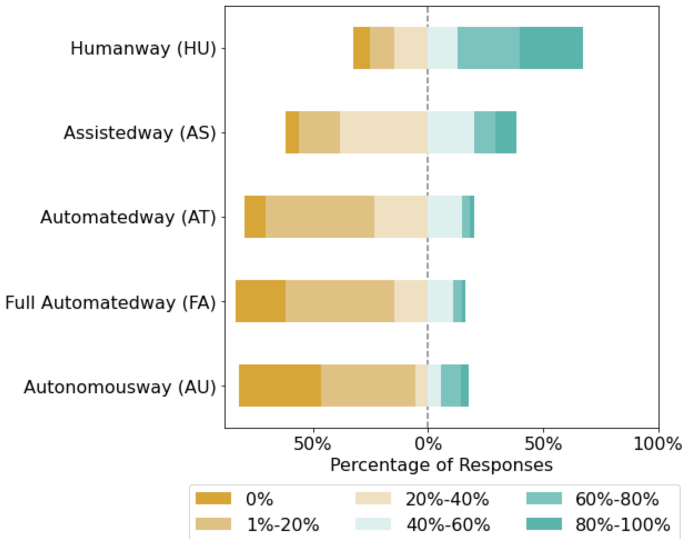

Figure 48. Expected percentage of every SRL in the near future.

1.1.1.25 5.2.2.5. *Automotive industry & SRC*

One of the most important stakeholders for the development and deployment of the SRC is the automotive industry. As concluded in Questionnaire 2, the industry has not provided much information, so far, about the operating characteristics of the systems and vehicles they are developing due mainly to such information would be of interest to competitors and could affect investors. **Despite the great effort to contact companies in the sector, only one response has been obtained from the automotive industry in Questionnaire 3**. Therefore, the conclusions obtained from the analysis of this questionnaire must be considered with caution, being necessary to involve this stakeholder in future discussions.

To this regard, the questionnaire included some questions related to the benefits that would be achieved if certain information was shared with other stakeholders, especially with road administrations and operators. As a result, **approximately 70% of respondents (79% of RAs and ROs) consider necessary to know the Operational Design Domain of the vehicles to determine Operational Road Sections (ORSs)**. Regarding this, an important number of respondents pointed out that the best way to make the ODDs explicit is by means of open and collaborative platforms or making it mandatory through legislation.

Even more important, **nearly all respondents (>90%) agreed with automated vehicles should be required to report their disengagements**. To this regard, the collection and analysis of disengagements of automated vehicles should be open access for 72% of respondents.

These results support the importance of knowing the operation of current CAVs and where technology is evolving to better understand the studied phenomenon and define a more accurate road classification system. The comments of the respondents show a wide consensus that the automotive industry can participate in the development of the SRC by establishing a tight connection with road infrastructure and connectivity providers and making their ODDs explicit to serve as a basis for the determination of Operational Road Sections. To do this a reality, the SRC must be as simple as possible to avoid the rejection of this sector. In this context, there should be confidentiality guaranteed from the SRC developers.

It is worth noting that 80% of respondents considered that all physical and digital road infrastructure information should be shared to promote and encourage a variety of information providers which might be associated with the automotive industry. However, **RAs and ROs appeared to be more reluctant to share this information as only three out of four agreed on this issue**.

Moreover, respondents to Questionnaire 3 were asked for ideas to involve the automotive industry in the development of the SRC. Some of them are attached below:

"Similar to C-ITS deployment in Europe I would propose not to interact with single OEMs, but to collaborate with OEM driven platforms."

"(a) Provide detailed information on the infrastructure requirements for the various LOSAD and ISAD Levels, (b) Provide information on disengagements, to be considered for SRC levels estimation."

"Defining requirements for the infrastructure, with special attention to different scenarios and environments."

"Sharing information regarding the requirements and performance of their CAV systems and components. Obviously, there should be confidentiality guaranteed from the SRC developers. The incentives for such sharing include a level of consistency expected between the designed or produced CAV systems and the developed SRC."

"Industry must clearly identify and certify factors and thresholds characterizing ODD for theirs CAVs"

"Automotive industry may be engaged in the development of the SRC by establishing a tight connection with road infrastructure and connectivity providers and making their ODDs explicit to serve as a basis for the determination of operational road sectors (ORSs)."

"The work on SRC should be a collaboration and exchange between the road authorities and the Automotive industry. It should be a process of exploring the weaknesses together which should be strengthened even from the side of the automotive industry or could be supported by the road authority."

1.1.1.26 5.2.2.6. Communicating SRC to road users

In addition of the benefits of the SRC for Road Administrations and Operators, the SRC is intended to be used by road users. Thus, Questionnaire 3 included an open-ended question to identify the best way to convey the SRC framework to drivers.

The responses of the participants pointed out that **the system should be considered as a part of the training to get the driving license**. Furthermore, respondents insisted on the **necessity to create new road signs to communicate the Smart Road Level** (SRL) of a road section to road users. Related to this, an important number of responses highlighted the benefits to include the SRL in HD maps and the importance of stablishing standard messages to clearly transfer this information to drivers by means of Human Machine Interfaces (HMI).

Some of the comments gathered on this issue are:

"Variable roadside signaling and in-vehicle application notification (visual and voice)."

"On the driver's license and in the media and social networks."

"Simply as possible, starting from driving schools then also as a package buying a CAV. Also, road operators shall promote is as possible (TV, internet, service areas, etc.)"

"GPS navigation system may include this information as criteria for routing."

1.1.1.27 5.2.2.7. Benefits and opportunities

Respondents to Questionnaire 3 were asked for the benefits and opportunities of using the SRC. Despite the great variety of responses, five main pillars were identified from the respondents' answers: (i) road safety improvement, (ii) quicklier CAVs integration, (iii) more sustainable transport, (iv) improvement of traffic operation, and (v) efficient allocation of road investments. Some comments in Questionnaire 3 related to these pillars are:

"Ensuring safety and accelerating autonomous driving thanks to regulations."

"Multiple; from increasing user confidence to business opportunities for technology companies, with the capacity to generate a lot of employment."

"Low emissions, better road safety, higher level of service with the same infrastructure."

"Accelerate the spread of CAVs, stimulate road operators and industry to improve their systems SRC maps are useful for making users aware of the availability of a road network adapted for CAVs. For operation, SRC and ODD must be part of the data used by the navigation tools to select the best route from Origin to Destination."

These pillars are interrelated with each other in such a way that the implementation of the system will lead to a reduction of the number of crashes as the integration of CAVs becomes easier and faster and the traffic operation enhances. In this way, the SRC will encourage a more sustainable transport system as vehicle emissions are expected to be decreased. Furthermore, the system will allow Road Administrations and Operators to efficiently allocate road investments, maximizing CAVs integration.

1.1.1.28 5.2.2.8. Challenges and barriers

Although major benefits are expected from the implementation of the SRC, people participating in Questionnaire 3 also identified significant challenges and barriers. Undoubtedly, the implementation of the system requires a great investment and not all stakeholders are willing to carry it out. A great proportion of responses agreed with the need of stablishing a common legal framework that supports the harmonization of the ODDs and defines those aspects related to stakeholders' liability.

One of the most important challenges is to make all stakeholders work towards a common goal. To this regard, most respondents considered the active collaboration of the automotive industry of greatest interest. However, some of participants also reported the difficulty associated with data management mainly because the great amount of information to be managed and the conflicts of interests that might arise between automakers.

Other challenges to take into account are the technological progress, that is constantly evolving, and the need to fund research, that would allow Road Administrations and Operators to adapt the system over time. Additionally, some specific features of developing countries –i.e., the old fleet of vehicles– might make the system useless.

According to the respondents' comments, important barriers to the implementation of the system might be its complexity and social acceptance. To this regard, it is important to note that some objectives of the SRC –i.e., common language, consistent, simple, and credible– aims at addressing these issues.

Below, some of the most interesting comments on the challenges and barriers for the deployment of the system are presented:

"Multiple stakeholders and no specific guidelines to date. The transition period with different mix of SAE levels."
"Funding, regulations, and user acceptance."
"Conflicting interests of automakers and related industries, uncertainties about the further progress in the CAVs area, strong diversification of technology, use of vehicles, culture of driving, road management across countries."
"Legislation framework and liability. Research needs. Costs for road rehabilitation and maintenance of both physical and digital infrastructures and C-ITS services."
"Low level of standardization, certification, regulation and communication coverage."
"Cooperation with the automobile industry."

1.1.1.29 5.2.2.9. Application

The application of the SRC system was surveyed considering two perspectives: (i) planning and investment stage and (ii) management stage. At planning and investment stage, the respondents highlighted the need to stablish short-, medium-, and long-term goals. To this regard, high SRL roads should be prioritized to perform pilot tests. Moreover, some responses indicated that a methodological guide would ease the application of the system because it might be complex or difficult at an early stage.

On the other hand, sharing information among stakeholders seems crucial at the management stage. To do this, some respondents pointed out that the creation of new management centers and the standardization of the information would facilitate data exchange. At this stage, the communication of the Smart Road Level becomes a key aspect. According to the responses retrieved in the questionnaire, Road Administrations and Operators should encourage the increase of Smart Road Levels along the road network over time.

5.2.3. Comparative analysis between Questionnaire 3 and webinars

A total of 162 and 40 people participated in the webinars organized by PIARC and the Spanish National Committee of PIARC, respectively. Whereas the PIARC's webinar aimed to cover as many countries as possible, the webinar held in Madrid was organized at a national level. In this way, people from 67 countries were registered to attend the PIARC's webinar.

Figure 49 and Figure 50 show the distribution of the attendees by stakeholders. During both webinars, some questions or items included in Questionnaire 3 were proposed to be answered by the attendees. In this way, this section aims at comparing the main findings of Questionnaire 3 with those obtained in the webinars.

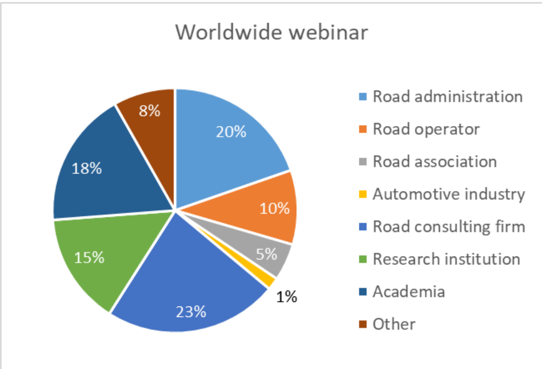

Figure 49. Percentage of responses to worldwide webinar by stakeholder.

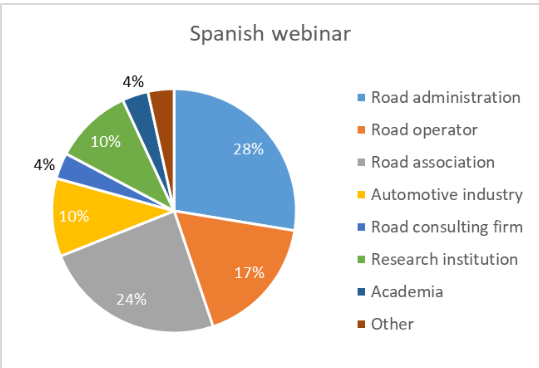

Figure 50. Percentage of responses to Spanish webinar by stakeholder.

Table 28 summarizes the findings obtained for some global aspects of the proposed SRC. First of all, it should be noted that most attendees in the webinars considered the SRC system needed for the deployment of CAVs which was consistent with the response retrieved in Questionnaire 3. As expected, the level of understanding of the proposal was slightly higher during the webinars as the UPV Team explained the different parts of the proposal by means of video presentations. This fact also impacted on the level of detail, retrieving a better result in the Spanish webinar than in Questionnaire 3. While the response of the applicability of the proposed Smart Roads Classification was very consistent –3.5/5–, people attending the worldwide webinar were more cautious about the deployment of the system in the near future.

Question	Questionnaire 3	Worldwide webinar	Spanish webinar (1-5)
Necessity of SRC for CAVs deployment	80%	83%	4.61
Level of understanding	3.57	3.60	3.89
Deployment in the near future	4.16	3.83	4.69
Applicability	3.48	3.59	3.56
Level of detail	3.47	-	4.05

Table 28. Comparison of findings for global aspects.

Regarding the objectives of the SRC system, both webinars presented the same trend as that obtained in Questionnaire 3 (Table 29). Thus, the objective that raised the most doubts was that related to liability, although the attendees to the webinars showed a greater degree of agreement (48%-61%) than the respondents to Questionnaire 3 (41%). There is a consensus that the responsibility for establishing and updating the Smart Road Levels should lie with Road Administrations and Operators. Moreover, the responsibility for using the Smart Road Levels seems to be shared between users and automated vehicles (Table 29).

Question	Questionnaire 3	Worldwide webinar	Spanish webinar
Agreement with no liability for RA/RO objective	41%	61%	48%
Responsibility for establishing and updating	RA & RO (75% & 58%)	RA & RO (77% & 58%)	RA & RO (65% & 70%)
Responsibility for using	User: 51% AV: 35% RA: 29% RO: 31%	User: 35% AV: 41% RA: 29% RO: 27%	User: 57% AV: 39% RA: 17% RO: 22%

Table 29. Comparison of findings about liability.

Last but not least, Table 30 shows the main findings concerning the importance of the automotive industry in relation to the exploration and development of a new Smart Roads Classification. As in

Questionnaire 3, most of the webinar attendees considered that specific information that could be provided by the automotive industry, such as the Operational Design Domain and the report of disengagement of the vehicles, would encourage a more sophisticated and accurate system. Additionally, the responses to the Questionnaire 3 and webinars supported the idea that all physical and dynamic infrastructure information should be shared to boost its use by information providers which would likely lead to new business models.

Question	Questionnaire 3	Worldwide webinar	Spanish webinar (1-5)
Explicit ODDs	70%	84%	4.54
Report disengagements	95%	88%	4.75
Sharing infrastructure information	86%	88%	4.54

Table 30. Comparison of findings related to the automotive industry.

5.3. SRC Model

The Smart Roads Classification, as a model, will be determined in terms of two indicators related to autonomous performance and connectivity support: LOSAD and ISAD. Both of them are based on explicit indicators that could be retrieved by Road Administrations (RAs). The indicator for the automation level is the **L**evel **O**f **S**ervice for **A**utomated **D**riving (**LOSAD**), proposed by the HERG [7], while the indicator for the connectivity level is the **I**nfrastructure **S**upport Levels for **A**utomated **D**riving (**ISAD**), proposed in the INFRAMIX project [17].

Nevertheless, it is important to note that the requirements associated with the SRC system are completely independent of those that, in the near future, will be defined to approve or certificate CAVs performance.

5.3.1. LOSAD levels

The proposed LOSAD is categorized in five levels, from A to E. It is determined as a function of how ready the road infrastructure is to support automated driving. The most important parameter to define the LOSAD of a road segment is the distribution of their Operational Road Sections. As seen in section 3.4, an Operational Road Section (ORS) can be defined as a section that fully supports automation for all driving automation systems with explicit ODDs. In other words, a section that should be ideally driven by any driving automation system. According to the SAE definition for the different levels of automation, a disengagement-free trip can only be ensured for level 4 (within their ODD sections) and for level 5. Levels 1 to 3 may present disengagements even within their ODDs, so disengagement-free trips can never be ensured.

Therefore, the LOSAD level will be mainly influenced by low SAE level 2 and 3 vehicles as long as very different vehicles share the road space. Vehicles with a higher level of automation will have the detailed characteristics of the physical road infrastructure, so they could even maintain their automated control on road sections with a more limited LOSAD, always under their responsibility, since the SRC is an informative road classification system.

Before addressing the LOSAD concept, it is necessary to clarify what road segments and sections are in these definitions. A road segment is the road portion delimited by major intersections or an urban environment. Driveways and minor intersections may or may not suppose a road segment change. A road section refers to the minimal portion of the road that presents identical factors, including geometry, cross section, environment, and the like. Every horizontal curve –as well as short tangents– should not be divided into different sections. A long tangent may be divided into different sections if some important property differs on it.

The proposed SRC is designed to be applied to road segments, but also to intersection roadways and interchange ramps. The latter roadways correspond to road segments with a unique road section in the SRC model hereinafter.

As the percentage of the road segment that does not belong to an Operational Road Section (ORS) increases, LOSAD will decrease given that high automated vehicles will present lower opportunities to drive autonomously. LOSAD also decreases as ORSs become shorter. The following levels are proposed:

- **LOSAD A**: The road segment presents a continuous ORS that ensures a safe automated driving for high automated vehicles (levels 4-5). Levels 2 and 3 should perform with minimum disengagements due to their lower technology, i.e., a disengagement-free driving cannot be ensured from the infrastructure side (although their number would be very low or null).
- **LOSAD B**: Like for LOSAD A, the road segment is composed of a single ORS that must keep in automation all SAE level 4 and 5 vehicles. However, dynamic conditions such as weather may temporarily limit the ORS effectiveness. The LOSAD B also appears if the number of disengagements exceeds a given threshold, mostly caused by SAE level 2 and 3 vehicles.
- **LOSAD C-D**: These levels are characterized by a non-continuous ORS within the road segment. The final level will depend on the number and length of ORSs along the segment. Most drivers may need to retake manual control of their vehicles at the non-ORSs. A minimum disengagement rate might also be expected within ORS, as for previous levels. In addition, adverse weather conditions might also trigger LOSAD C or LOSAD D conditions. Specific thresholds are still to be researched in the future, depending on how diverse CAVs are, the minimum period of time that would be adequate to be under automatic control, etc.
- **LOSAD E**: There are no ORSs, or their length is too short to ensure comfortable automated driving. Therefore, most drivers of SAE level 3 and 4 vehicles might be willing not to activate their systems. Drivers of SAE level 2 vehicles would not experience any remarkable benefit from lane keeping assistance, given that it would be disengaged most of the time.

The LOSAD classification is dynamic. Therefore, a road segment would have a LOSAD category upon the static factors that may downgrade to a lower one if triggered by any dynamic factor (e.g., disengagements and weather conditions). Two examples are given for clarification purposes:

- A LOSAD A road segment might temporarily shift to B if many disengagements are observed within a section, regardless the triggering factor (it may even be unknown). The level of the driving automation systems suffering disengagements is not relevant in this case.
- A LOSAD B road segment might temporarily shift to D if a sudden, violent rainfall takes place. Heavy rain has two effects: (i) creates a layer of water that may affect automation (this also depends on the drainage conditions), and (ii) limits visibility. The limitation of visibility might also be detected using the Visibility factor. These conditions might also trigger a high number of disengagements, which could be detected using the corresponding factor as well.

Instead of maintaining the LOSAD level and only reporting the limiting dynamic factor, such as heavy rain, it is considered safer to reduce the LOSAD level temporarily. The user does not need to know the cause, since in addition, depending on the degree of limitation, such as the intensity of the rain, the LOSAD may not degrade even if the user perceives that there is some rain.

A new parameter, the disengagement rate, is necessary to apply one of the factors. This can be defined as the number of disengagements within ORSs divided by the volume of automated vehicles. Thus, it is a way of measuring how well the ORSs are performing, and a way to report unexpected or abnormal behavior of the road infrastructure and automated vehicles. If this indicator is finally established, it would be necessary that all automated vehicles report these events in real time, including position and time. Other data would be helpful in order to identify the triggering cause. Finally, this report should be provided by all vehicles from SAE level 2 to level 5. RAs would then combine data from all vehicles with additional information (e.g., weather, traffic, etc.), obtaining 'disengagement maps' for the road network for a variety of situations.

The information from disengagements is considered to be very important, since it reflects how CAVs are performing along the road segment. Unlike establishing LOSAD based on geometric and environmental factors, this parameter would reflect the consequences of unknown factors affecting CAV performance. Not only would this information be useful to more accurately tag the LOSAD of the road segment, but it would also help research overcome these limitations, and therefore expand ORSs.

Despite these benefits, all SAE level 2+ vehicles should be legally enforced to provide this information, and RAs should support a detailed, continuously updated road HD map. **This is neither the situation nowadays nor it will be in the short-term**. Once that day comes, a strong effort should be made by Road Administrations to establish an effective way to collect it. If this information is not ever published, alternative protocols should be defined to privately or partially collect these data with the same objective.

The proposed LOSAD factors can be consulted in Appendix A2. LOSAD and ISAD factors.

5.3.2. ISAD levels

Like LOSAD, the **ISAD is categorized in five levels** (A-E), **being A the highest connectivity support level, to E a conventional infrastructure.** These are the following:

- **ISAD A**: Support for cooperative driving, in which the infrastructure is fully capable of perceiving the behavior of all vehicles and guiding the traffic to guarantee efficiency and safety.
- **ISAD B**: Support for cooperative perception, in which the infrastructure can perceive some microscopic traffic situations and communicate with vehicles. There is some level of cooperation but still not with a full range of situations.
- **ISAD C**: Dynamic digital information, in which the infrastructure can modify the information of road variable message signs depending on weather or incident warnings.
- **ISAD D**: Static digital information/map support, which means that in this case the infrastructure provider –Road Administration or Operator– supplies to the vehicles along the area with digital map data complemented by physical reference points.
- **ISAD E**: Conventional infrastructure with no digital support, referring to today's roads in which there is not any digital infrastructure data and, therefore, no explicit Automated Vehicle support is provided.

These descriptions were introduced by the InfraMIX project [17]. Most of them refer to the data requirements of the digital infrastructure, with lower attention to the physical part of the infrastructure, or the connectivity requirements.

Like the LOSAD classification, the ISAD one is also dynamic. In this case, factors such as the DSRC/ITS-G5 range may deprecate the connectivity support, reducing the ISAD level from the base one given by static factors.

The proposed ISAD factors can be consulted in Appendix A2. LOSAD and ISAD factors.

5.3.3. Smart Road Levels

The different LOSAD and ISAD levels provide road segments with different characteristics related to automated and connected driving. Moreover, some interactions of these levels generate synergies that are especially interesting for Road Administrations and Operators.

As a consequence of the various interactions, **five different types of Smart Road segments can be distinguished with specific characteristics related to CAVs**. Although there are 25 possible combinations of the different LOSAD and ISAD levels, some of them are very similar and can be grouped together. From lower to higher CAV support, these five levels are:

1. **Humanway (HU).** The road is not ready for CAVs. This means that SAE level 2 and 3 vehicles would experience too many disengagements, prompting their drivers to manually disconnect the system. These segments would not present ORSs, and SAE level 4 vehicles may not find clear ODDs –this would depend on the specific technology of the ADS– and will generally perform in manual mode. A SAE level 5 vehicle would be able to operate along this road –given that these vehicles are ODD-free– but connectivity to infrastructure is not guaranteed. However, even for these high-end vehicles, performance, operation, and safety might be compromised as well, if they cannot operate at a reasonable speed.
2. **Assistedway (AS).** The road is adequate for SAE level 2+ vehicles, meaning that it would not induce too many disengagements to levels 2-3. This would allow drivers to enable their driving automation systems. Road Administrations should put special focus on ORS discontinuities and any other disengagement-prone location, to prevent driver distractions, especially for SAE level 3. While more extensive ODDs can be found compared to HU, the road segment might be divided into many ORSs that do not provide a comfortable and automated driving experience for SAE level 4 vehicles, limited by the physical infrastructure or the connectivity capabilities (the road cannot provide detailed information about the dynamic parameters that should be compared to ODDs).
3. **Automatedway (AT).** The road segment presents better characteristics than AS segments, especially related to connectivity. These road segments present HD maps and can transmit digital information to CAVs, so these can better identify ODD-related factors and ODD terminals. In addition, less and more continuous ORSs can be found within. SAE level 2 vehicles would experience less disengagements than on AS segments, and SAE level 3 vehicles would be able to use the digital information to foresee oncoming disengagements. The longer ORSs would allow a better, longer performance of SAE level 4 vehicles in automated mode.
4. **Full Automatedway (FA).** The road segment presents a continuous ORS, so all SAE level 4 vehicles should be able to operate autonomously along the entire segment. In addition, these segments present safe harbors –including their junctions to other segments–. While the ORS is not directly related to SAE level 2 and 3 vehicles –these are not required to explicit their

ODDs– a much lower number of disengagements compared to AT is also expected. Connectivity is even better than AT segments, facilitating cooperative perception and including all safe harbors in the HD map. All road users would benefit from better global performance and safety levels.

5. **Autonomousway (AU).** The road segment presents similar physical conditions than the FA segments –i.e., complete ORS along the segment, safe harbors, etc.–, and incorporates exceptional connectivity features that enable cooperative driving. In order to benefit from the best performance and safety levels, only SAE level 4+ should operate along these road facilities or with dedicated lanes. The HD maps will also have very detailed information about the safe harbors –not only their presence but also their capacity and availability of free spaces–.

A diamond-shaped chart is proposed to identify the smart level of the road as a function of LOSAD and ISAD (Figure 51). The shape of the diagram has been carefully developed, keeping ISAD and LOSAD separately and showing any improvement in the smart level of a road following a bottom-to-top path. While this chart presents all plausible combinations of LOSAD and ISAD, not all of them seem reasonable, i.e., cooperative driving support should never be provided to a road that cannot be driven by automated vehicles. These inadequate combinations have been cleared with a white pattern and identified with an asterisk.

This proposal establishes a framework that should be adapted to the specific circumstances of every country/region. These circumstances are related to the kind of parameters that could be retrieved from users/vehicles, national laws, enforcement level, characteristics of the road network (total length, type of infrastructure, etc.), existence of technology related to V2X communication, and budgetary restrictions, among others. The bottom part of the chart presents two percentage scales for ISAD and LOSAD, corresponding with the cumulative percentage of the road network. This can be used by Road Administrations and Operators to deduct the distribution of the smart levels as a function of the LOSAD/ISAD distribution. More detail about this procedure is later provided.

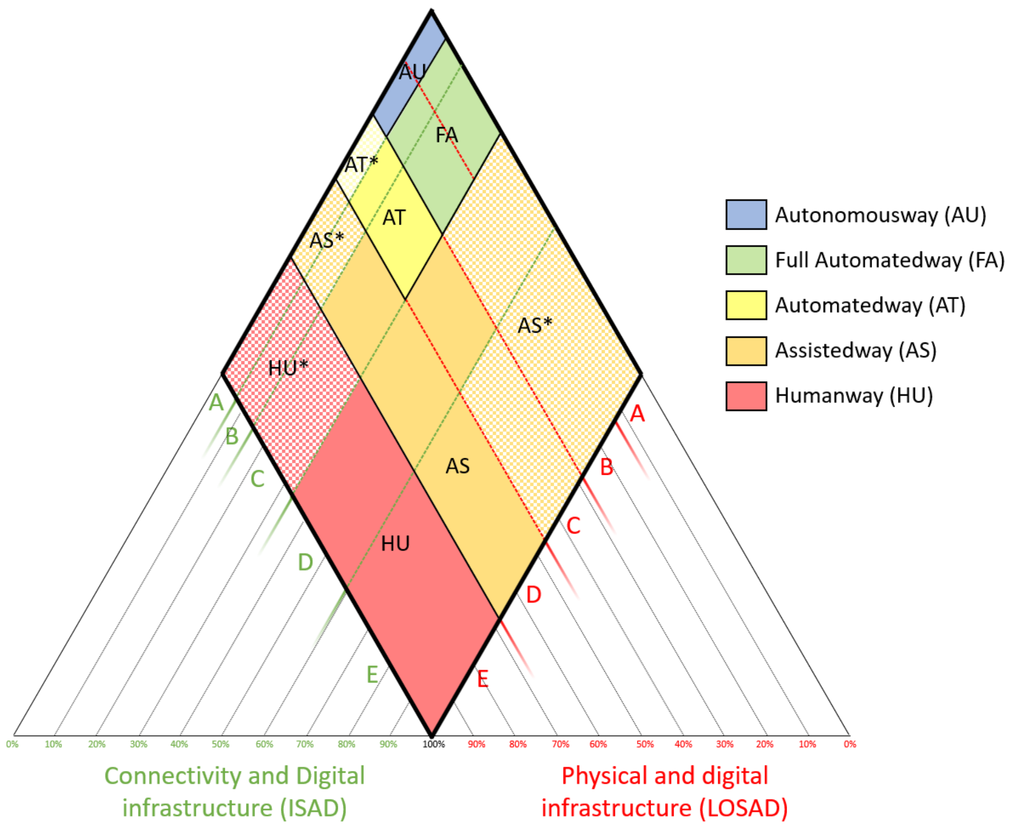

Figure 51. Diamond chart for the Smart Roads Classification.

In addition, the smart level can be used in line with the traditional classification system (i.e., in terms of mobility and accessibility), and with the classification systems involving users [2].

Although aggregated, every single zone of the LOSAD/ISAD combination might present some differences compared to the general description of the Smart Road Level (SRL). These differences are minimum but can be seen in Figure 52.

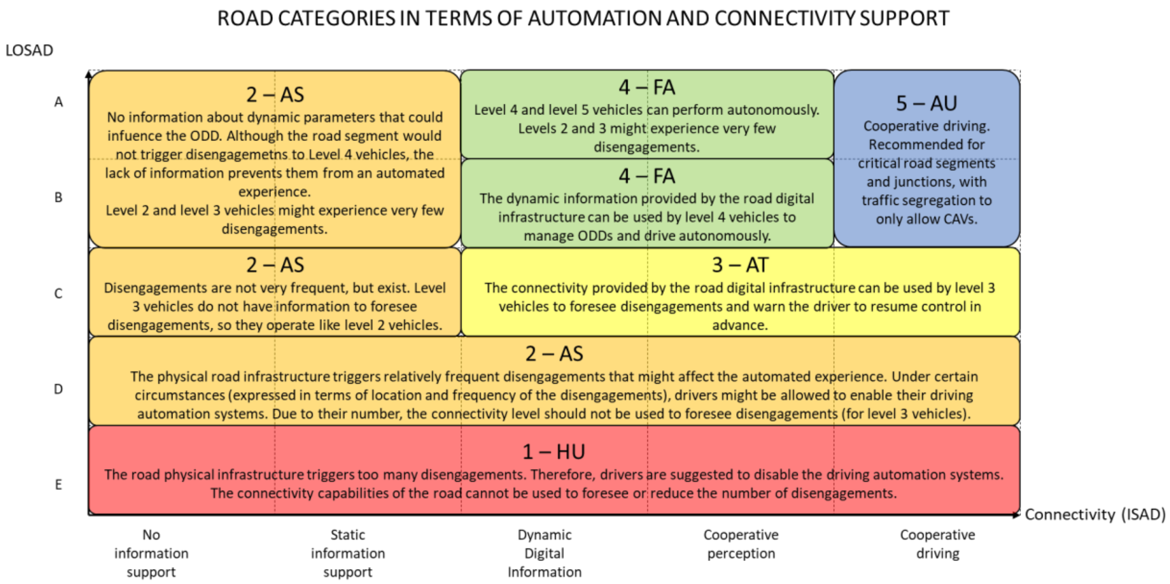

Figure 52. Description of the particularities of any ISAD/LOSAD combination. Minimum differences within the same SRC level can be seen.

Figure 53 represents the concept map of the SRC proposal, indicating the input factors from the different layers and the interaction with other classification systems. As it can be seen, ISAD and LOSAD can be used to determine the Smart Road Level (SRL), but the underlying factors can be used as well without prior determination of ISAD and LOSAD.

Given that there are static and dynamic factors, road segments would have a static-based smart level, as a reference, that may be downgraded due to any dynamic factor.

In addition, the SRC is also connected to other existing classifications (road typology and the expanded classification including users). In fact, connectivity and/or automation create new kinds of user interactions. Traffic volume and composition are another group of factors that affect the infrastructure management.

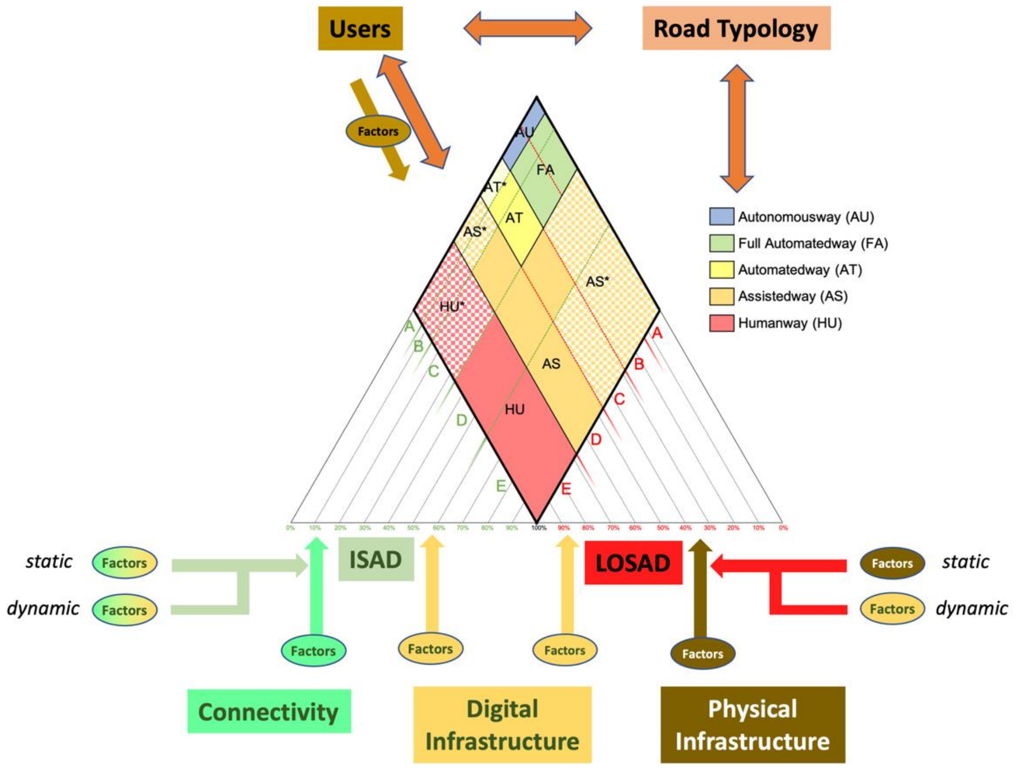

Figure *53. Smart Roads Classification, including source data and interaction with other road classification systems.*

Users should be able to perform along every type of road segment, except SRL 5 (AU). This one uses the cooperative driving advantages, which require automation and connectivity. Therefore, these road segments should be restricted to very specific zones –or dedicated lanes– for which cooperative driving supposes a great improvement in terms of safety and/or performance. SRL 4 road segments (FA) may not have any limitation regarding road users, but probably these road segments would apply to freeways and high-end two-lane rural roads. Therefore, Road Administrations and Operators would be likely to prohibit certain users (e.g., pedestrians, bicycles and LMV) as they do today.

It is worth to mention that the benefits for CAVs would also depend on the interaction between the SAE and the SRL. The implementation of this system, however, should not wait explicit ODD definitions. Instead, Road Administrations and Operators should define the SRL for their road segments –or at least their best road segments– and let drivers decide whether they activate automation or not. It is important to remind that the ultimate responsibility of the driving task is the driver –either human or vehicle– and Administrations and Operators should only provide the road segment characteristics for information purposes. Moreover, automated vehicles should not ever just rely on data transmitted from the infrastructure side. They should compare this information in a redundant way to what they perceive with their sensors.

5.4. Factors

The direct application of LOSAD and ISAD concepts can be used by Road Administrations and Operators to determine the SRL of a road segment. This is called the **main classification system.**

However, for management purposes, the LOSAD/ISAD-based classification may not be the best option since it requires determining both indicators first. This is why all different, underlying factors related to LOSAD and ISAD are necessary to be developed. These ones constitute a sort of checklist that could be used by Road Administrators and Operators to determine the smart level of their road segments. This has been named as **detailed classification system.**

As indicated at the introduction of section 5, a more comprehensive tables including specifications for every smart road level is provided (see Appendix A3. SRC factors). These tables summarize all LOSAD and ISAD factors and provides additional detail related to how ORSs should be materialized. While most ORS factors should be further researched, a few proposed values are given. In addition, the tables distinguish between the aspects that should be provided/ensured by Road Administrators and Operators, and the requirements that every vehicle within the road segment should meet –if automation is activated–. It is important to highlight that the driver –either human or vehicle– is the ultimate responsible for the driving task. Road administrations and operators should make explicit the available automated driving supporting road characteristics for every Smart Road Level (SRL) and the automated vehicle will decide whether it can switch on automated driving or not, according to the technologies it is equipped with. Therefore, RAs and ROs are responsible for road characteristics that support automated vehicles, but it will be the latter and their drivers who will take responsibility for how to maintain driving.

Appendix A3. SRC factors consists of diverse tables, for each proposed Smart Road Level, in which all factors have been grouped into the following categories:

- **Physical infrastructure**. This layer includes the road typology, the geometric design of the road, pavement characteristics, road signage, and all other physical aspects related to the road and its environment. Moreover, different speed concepts as performance indicators are included (e.g., speed limit, operating speed, automated speed).
- **Digital infrastructure**. This category summarizes the availability of information for drivers and vehicles, as well as the physical facilities that the road presents to comply with that purpose. It includes aspects such as the presence and typology of Variable Message Signs, existence of maps and inventory, digital signing, and road/data sensors such as weather, safe harbors, and Roadside Units (RSUs).
- **Connectivity**. This group summarizes the connectivity capabilities of the road, including the V2X protocols and possibilities, 5G coverage, capacity of cooperative driving, etc.
- **Users**. This layer is not part of the LOSAD and ISAD tables, but has been added to summarize the connectivity and automation implications for the potential users of the road facility.

Although many factors have been proposed, perhaps not all will be necessary for the final classification system.

5.5. Key Performance Indicators

Key Performance Indicators (KPIs) can be used by Road Administrations and Operators to know the performance situation of their road network and make strategic decisions, maximizing the outcome of their investments. There are many possible actions that can be planned to increase road safety and traffic performance, affecting the highest number of people and having a clear picture of the starting situation. Many of these KPIs are alternate and require different sources of data. KPIs can also be used to compare the situation of a road network longitudinally (i.e., in time) and to the road networks of other countries or regions.

Four groups of KPIs are proposed:

- Automation. This KPI refers to the distribution of the disengagement rates per every Smart Road Level, for the entire road network and for the main one. This indicator can be used to verify whether road segments with higher SRLs have fewer disengagements or not, and to assess differences between road networks.
- Safety. These KPIs focus on the average crash rate involving only CAVs of the road network and the ratio of CAVs Crash Rate to All vehicles Crash Rate, in order to identify if there is an over-representation of CAV crashes on the entire road network. To take into account of target reductions in fatal injuries, all casualties, and the KSI (Killed and Seriously Injured) data, these KPIs could be split.
- Operation. This KPI refers to the average TTI (Travel Time Index) of each Smart Road Level for the entire motorway/freeway/expressway network, as a traffic efficiency measure.
- Smart Road Level. This final group of KPIs relate to the distribution of the LOSAD, ISAD, and SRLs across the road network, based on static factors. It is especially interesting to see its current state and evolution in time. Comparisons between different regions of a Road Administration can be performed with them, as well.

Table 31 details the proposed KPIs for all groups. These primary KPIs can be used in calculations to obtain secondary KPIs that might be preferred by Road Administrations and Operators.

	KPI
Automation	Average distance driven (km or mi.) without disengagement per road segments of each smart road level, for the entire road network
	Average distance driven (km or mi.) without disengagement per road segments of each smart road level, for the entire motorway/freeway/expressway network
Safety	Average Crash Rate involving CAVs for the entire road network
	Ratio of average CAVs Crash Rate to all Vehicles Crash Rate, for the entire road network
Operation	Average TTI (Travel Time Index) of each smart road level for the entire motorway/freeway/expressway network
Smart road level	Percentage of each smart road level for the entire road network

	Percentage of each smart road level for the entire motorway/freeway/expressway network
	Percentage of each ISAD level for the entire road network
	Percentage of each ISAD level for the entire motorway/freeway/expressway network
	Percentage of each LOSAD level for the entire road network
	Percentage of each LOSAD level for the entire motorway/freeway/expressway network

Table 31. Key Performance Indicators.

Although disengagements and crashes not only depend on the Smart Roads Classification (SRC), but also on the construction and operation of automated vehicles, higher Smart Road Levels (SRLs) will facilitate their performance and, therefore, disengagements and crash rates are expected to be lower.

At this stage of exploration for an SRC, KPIs should be developed and agreed upon once this initial proposal as a baseline classification is tested, evaluated, and established.

6. FEASIBILITY STUDY OF AN SRC APPLICATION

The aim of this section is to indicate how likely a Smart Roads Classification (SRC) is to be applied. To do so, different analyses will be performed. It is important highlight the objectives of a Smart Roads Classification, outlined in section 1.2 Objectives.

First, the benefits and opportunities of having an SRC will be outlined. Many of them were identified and retrieved from the great feedback provided by means of Questionnaire 3 and webinars. A first general overview is given summarizing the most important feedback, followed by specific comments grouped by typology.

Second, challenges and barriers will be explored, following a similar structure. Again, many of them have been collected with Questionnaire 3. Some of these statements are open questions that will have to be solved in the future. Some others are part of the possible scenarios, which will be developed later on.

The following section indicates how the Smart Roads Classification proposal interacts with the existing road classification systems (according to road typology, functional classification, and road users). A short section is later provided to explain how the different SAE levels interact with the Smart Road Levels.

Next, the different stakeholders that may intervene in the process are introduced. This is a short introduction, as their role is further developed in the following section.

The Scenarios section is very important. The applicability of a Smart Roads Classification system requires to know the situation about CAVs, connectivity, digital infrastructure, and so on. Given the uncertainty on these aspects, eight different scenarios are provided, indicating a hypothetic situation. For each one, different possible interactions among the stakeholders are assessed in the Business models section. The advantages or disadvantages of using an SRC are highlighted by setting base scenarios without the SRC.

Finally, a specific study about the Low-Medium Income Countries (LMIC) is given, based on the considerations of the Scenarios and Business models sections.

6.1. Benefits and opportunities

The most relevant benefits and opportunities that have been identified are as follow:

- An SRC will contribute to an efficient planning of investments on physical and digital infrastructure and will promote a safer, efficient, sustainable, and comfortable road network.
- An SRC is a high-detailed comprehensive framework. Compared to other existing road classification systems, it can be real-time updatable. Since it focuses on an emerging technology, it will guide investment and system design much more effectively than traditional systems.
- In the near future, Road Administrations and/or Operator will have to inform users (including automated vehicles) about the road performance. There will also be a need to develop a system that indicates how this communication may be, and what information is collected and provided. An SRC could be used to clearly target these needs. Therefore, the SRC is expected to be a requirement, as users and CAVs will be willing to know about road performance.

  - An SRC could help create a common system for all countries, automotive industry, and other stakeholders. It could be used as a guiding inception, providing a basis for work and dialogue among stakeholders, especially between Road Administrations, Road Operators, and the automotive industry. An SRC should present a shared understanding of thoughts, approaches, terminology, conditions, and vision of future. It means an international standardization creating an accelerator/catalyst for change.

These are the specific benefits and opportunities grouped by classification:

- Safety:
  - Improvement of the road network safety, by indicating which road segments can be fully driven by fully Automated Vehicles, hence reducing the impact of driver improper behaviors.
  - Clear and simple indication of the Smart Road Level (SRL) for users, ensuring a free-of-surprises and safe ride.
  - Better route planning by users, who could choose itineraries in accordance with the characteristics of their driving automation systems, reducing risky maneuvers.
  - Work towards safe transitions between different automation levels (e.g., planning manual takeover requests, providing information about safe harbors, etc.).
  - If a road is classified as a Smart Road, it implies that more rigorous requirements are achieved, so it would be safer for both CAVs as well as non-CAVs.
- Operation:
  - Higher level of service with the same infrastructure thanks to increased capacity due to lower gaps between vehicles. This is especially applicable to the highest Smart Road Level (SRL), where only SAE 4+ CAVs are permitted.
  - More efficient traffic management and control. All stakeholders will know how they should interact with the infrastructure facilities depending on the SRL.
- Sustainability:
  - Improvement in environmental conditions. The more uniform speed profiles lead to lower number of speed variations, which is connected to emissions. This results in lower emissions and a better quality of life. Road segments with cooperative perception capabilities (FA and AU) could share information to vehicles that could be used for this purpose. Road segments with cooperative driving capabilities (AU) could also take control over vehicles to provide more uniform speeds.
- Infrastructure:
  - An SRC clearly identifies which roads are more likely to support CAVs. This helps administrations choose where to target investments, or which road segments should be recommended for drivers.
  - An SRC would work towards an optimization of the road infrastructure. This includes the digitalization of the road segments that are a priority to enhance safety and/or performance.
  - Increased uniformity and consistency in road design. Better SRL segments would present more uniform characteristics.
  - Stimulate Road Administrations and Operators to improve their road infrastructure and services. An SRC could be used to define an existing situation and compare it to other road networks or a future situation.

- Maintenance:
  - Better framework to establish a continuous reporting of road conditions. Depending on the SRL, this reporting could be obtained from the infrastructure, vehicles, or both. This would result in a continuous monitoring of the maintenance work and its optimization. Depending on the SRL, different ways of collecting and managing the information may exist. Clear maintenance response protocols could be established depending on the SRL of the road segment, providing a rapid response to serious deficiencies.
- Planning:
  - Simpler assessment of the status of a road network related to smart capabilities at a given time. A five-level Smart Roads Classification provides a rapid visualization and interpretation of the situation of the road network (e.g., percentage of AU road segments, existence of too many HU road segments, etc.). Please see Section 5.3 in which how the SRC diagram is used.
  - Tool to strategically help steer the investments to the essential road sections. Combined with other data sources –such as the CAVs Penetration Market Rate per zones– an SRC could be used to determine where an upgrade of road segments may have a higher return on investments. In other words, by identifying the synergies between road infrastructure and connectivity, an SRC also provides a better allocation of investments between vehicles and infrastructure.
  - RAs and ROs could compare and identify which road segments need upgrade. An SRC also constitutes a scale for the identification of more efficient investments based on evidence.
- Management:
  - The SRC is clear and can be applied straightforwardly. It may also be adjusted as the AV technology evolves. An SRC should be able to adapt to new CAV-related technologies that imply remarkable changes on how drivers and vehicles interact with the road.
  - CAVs should share information on events and incidents. Some SRLs are expected to be dynamic, changing the SRL of road segments. In this case, it is important that the SRC could adapt in real time.
- Automation:
  - Making the most of vehicle technology when possible. An SRC would ensure optimal (or at least better) performance of CAVs than not using the SRC. Connected vehicles compatible with the different SRL could use these properties to foresee disengagements and even prevent them. For SAE Level 4 vehicles, larger ODD-compliant zones could be defined.
  - An SRC would provide a greater clarity for the deployment of CAVs, stimulating industry to improve their systems towards clear road layouts. ODDs could have a real-world connection that may be used by OEMs to improve their systems.
  - An SRC could be used by OEMs to understand the level of penetration of the diverse Smart Road Levels, giving insight about the expected level of sales. The interest of consumers about connected vehicles may be triggered by the generalization of the SRL compatible with connectivity.
  - More tailored service to the Automated Vehicles. An SRC is a system comparable to SAE levels for automated driving.
- Users:
  - Facilitate users adapt their driving behavior to the road they are on, thus increasing safety.

  - Clear communication and framework, easily to understand by users.
  - Useful for making users aware of the availability of a road network adapted for CAVs. Users would see CAVs as a more useful and reliable technology, probably increasing their interest on purchasing/renting them.
  - Better use of CAVs by their proper routing through the road network using an SRC as part of the navigation tools.
  - Understand whether any smart roads offered will be useful and therefore whether to invest in high level of automation in vehicles.
- Others:
  - Improved communication among involved parties, helping build better standards.
  - An SRC would help all stakeholders understand the needs to take actions to make a functional progressive implementation of CAVs.
  - Possibilities for future new services. Some of these services may apply to some SRLs.
  - New business opportunities for technology companies, with the capacity to generate a lot of employment.
  - An SRC would involve insurance companies and telecommunication companies as well. They could anticipate somehow investments to create specific services based on Smart Road Infrastructure (not only on CAVs).

6.2. CHALLENGES AND BARRIERS

The most demanding challenges and barriers that have been identified are as follow:

  - Probably, the most important challenge to address is the lack of coordination and cooperation between the stakeholders that must intervene (i.e., those related to infrastructure, vehicle, and connectivity). Automakers have shown a big reluctance to explicit the limitations of their driving automation systems, which can be interpreted as a consequence of confidentiality. Moreover, automakers are probably willing to develop driving automation systems that can perform with no information from the infrastructure side at all. Although not today, the future ecosystem will require Connected and Automated Vehicles that receive/share information through a digital infrastructure. This information will include, but will not be limited to, data about micro and macroscopic performance that should be managed from the infrastructure side. The sooner this interdependence is established, the faster vehicles and road infrastructure will converge.
  - From the infrastructure side, a lot of work can be done to adapt to Automated Vehicles. Most of this work deals with harmonization of the discrepancies among different road authorities within the same or adjacent regions. An SRC should be flexible to these discrepancies, being a common system everywhere. While vehicles can adapt to these differences, this harmonization will reduce the dependence of digital information. This harmonization does not mean converging to common regulations, but to identify which of the current regulations are critical and should be revised. Compatibility with human drivers –who are used to the existing ones– should also be kept.
  - Consistency between the existing road classification systems and an SRC will have to be strengthened. There may be heterogeneity between countries/regions for the same Smart Road Level, either in terms of implementation, maintenance, etc.
  - There may be resistance to change from stakeholders of the current road system in the world. The necessary legislative framework must include the distribution or assignment of

liabilities. A clear leadership on the part of road authorities should be established. One of the objectives would be to minimize the constraints arising from a varying level of adoption among the different Road Administrations, both across regions and internationally, through the sharing of experiences and best practices.

  - A very important barrier to overcome is the implementation cost. Smart roads legislation and incorporation into the political agenda will be necessary, especially for the implementation of the first smart roads. An SRC, indeed, could contribute to identify which investments present the highest benefit/cost rates. Therefore, an SRC may be seen as a benefit and not as a challenge. Further explanation has been added in Section 6.7.
  - There is a high inertia of vehicle fleet with low renewal rate, which makes the Penetration Market Rate of CAVs a slow and long transition phase. Adequate management of the transition period, in which automated and human-driven vehicles will be on the road simultaneously, will be necessary. In addition, there is a high uncertainty about future CAV developments, including a strong diversification of technology, vehicle use, driving culture, road management in different countries, etc. This impacts on how an SRC is applied, and how the thresholds of the different levels are defined and updated.
  - For the application of an SRC, there are many research and study needs. Pilot tests remain as a key factor, where the cutting-edge capabilities of connectivity and automation can be checked on existing road facilities and under real-world traffic conditions. Finally, experts in new fields have to be trained all over the world about how to apply an SRC.

These are the specific challenges and barriers grouped by classification:

- Safety:
  - One of the most important benefits of an SRC would be a global safety improvement. Thus, the safety evaluation of any SRC that would be implemented should be obtained. The hypothesis to check is that by clearly indicating the smart properties of a road segment, users would enable/disable their driving automation systems.
  - The lowest SRLs (HU, AS) should have clear effects on levels 2-3 vehicles. This is key to expanding user acceptance and, therefore, a higher safety level when enabling/disabling these systems. More levels may be added, if needed, while keeping a simple understanding by drivers.
- Sustainability:
  - It should be demonstrated that differentiating the high-end SRL (i.e., AU road segments) results in lower emissions due to cooperative driving.
- Operation:
  - An SRC should be applicable to a variety of regions and traffic conditions.
- Infrastructure:
  - As indicated above, the deployment costs are very important. It would be necessary to determine who pays or invests for what. This may differ across countries and vary in time.
  - An SRC should be applicable to a variety of regions and traffic conditions. This includes adaptation to the existing infrastructure and user needs.
  - The necessary complexity of the new road system would be benefited with the standardization of road infrastructures. While not changing the existing standards, new regulations should converge in some points that enhance harmonization.

  - Two-lane roads with multiple accesses, intersections, and complex layouts may be more difficult for an SRC application, if many SRL alternate in a short road length.
- Planning:
  - The cost/benefit ratio over time must be considered for investment decisions. It will be necessary to study the possible ways of obtaining income to make the important investments more feasible.
  - Considering the high cost of digital infrastructure, the uncertain scenario and the fast technological development of connectivity solutions, a rapid implementation of a given technology is discouraged. Only no-regret measures should be implemented. Here, 'no-regret measure' refers to a road measure that would not become obsolete a few years after implementation. Long-term vision is necessary to distinguish which investments would comply with this point.
- Maintenance:
  - The way roads are planned and maintained today must be completely changed. Road rehabilitation and maintenance costs are expected to be high, including those related to physical and digital infrastructures, as well as connectivity. This change could be different as a function of the SRL.
  - The economic commitments between the different decision-makers and road users related to maintenance will change.
  - A sustainable financing model for maintenance and rehabilitation should be established. The model should cover, among other aspects, which should be the minimum ordinary investment, or how to deal with the different Smart Road Levels.
- Management:
  - It should be established who controls the SRC requirements by Road Administrations and Road Operators. This includes the factors and thresholds for the different SRLs.
  - A regular assessment and update of the estimated SRLs will be required, to reflect possible changes due to maintenance, new AV requirements, etc.
  - The existence of many dynamic factors may result in a very complex classification process. Clear protocols and responsibilities should be established. This includes the establishment and revision of the certification processes that may be required for vehicles and roads.
  - In addition, an updating protocol for any SRC itself should be established, including the most recent improvements of the infrastructure, connectivity, and CAV technology.
  - Handling of multiple large-scale data from multiple interconnected sensors and vehicles, which will require information management centers based on data science and artificial intelligence. The information must be reliable and be verified by the road manager with the necessary compatibility with data from road infrastructure sensors and the detection sites. Again, the verification framework is expected to depend on the SRL.
- Automation:
  - There is uncertainty about future CAV developments, strong diversification of technology, vehicle use, driving culture, road management in different countries, etc.
  - The conflict of interests among automakers and related industries may hinder data sharing, including disengagements, that could speed up the adaptation of the infrastructure to vehicles. This is not only limited to data sharing but to CAV operation (how well do automated systems perform).

    - The long transition period with mixed traffic of different SAE levels clearly affects the development and implementation of an SRC. Every SRL should be compatible with all vehicles. This does not only refer to the particularities of every SAE level, but also to the heterogeneity among the ODD of vehicles.
    - OEMs may not adopt an SRC if the SRC proposal is too complex. Easy instructions should be developed so the driving automation systems can determine how to proceed upon the SRL of the road segment.
- Users:
    - A critical issue is that an SRC should be direct and easy to interpret by users. It should be effective to increase social acceptance. Information and education campaigns should go in hand with the application of an SRC, explaining what an SRC and the vehicles can do and what not.
    - Ongoing concerns about cyber security may reduce the user acceptance of CAVs.
    - An SRC should not limit its applicability to CAVs, but also extend it to other users such as human-driven vehicles, pedestrians, cyclists, agricultural traffic, access movements, wildlife, ...
- Others:
    - An SRC must be technology agnostic. It should only focus on the provided service to vehicles, regardless how it is provided. This affects some factors and thresholds. Moreover, the different technologies may complement each other at many locations, so interoperability among them should be considered.
    - CAVs will operate worldwide. Regardless how fast is this transition, all countries should move towards applying an SRC. Ensuring a homogeneous solution is necessary to expand its applicability.
    - The scope of an SRC should be expanded in the future to suburban roads and urban roads and streets. These environments present much more complex ODDs.

6.3. INTERACTION WITH EXISTING ROAD CLASSIFICATION SYSTEMS

The SRC can be combined with existing classification systems, being an important input for Road Administrations (RAs) for planning and management. This section explains the relationship between the proposed classification and road typology, the functional classification, and road users.

6.3.1. Road typology

The Smart Roads Classification can be applied to many different road types. Some combinations are preferred given their higher benefit/cost ratios. Higher Smart Road Levels (SRLs) should be applied to road segments showing higher traffic volumes or with traffic performance concerns.

These combinations will change in time as the technological development would gradually increase the SRL of the roads. RAs could actively target certain road segments to apply low-cost measures to the physical infrastructure or improve the connectivity capabilities. This would enhance the LOSAD/ISAD levels. In addition, as more advanced driving automation systems hit the market, disengagements would become less frequent, increasing the LOSAD level and therefore the SRL.

Therefore, the recommended relationship between road typology and SRL should be variable in time. Figure 54 describes two situations: a recommendation for a near-existing situation (e.g., year 2025), and a foreseeable situation in the future.

	HU	AS	AT	FA	AU
Motorway				X	X
Freeway			X	X	
Multilane		X	X		
Two-lane	X	X			

	HU	AS	AT	FA	AU
Motorway				X	X
Freeway				X	X
Multilane			X	X	
Two-lane		X	X	X	

Figure 54. Adequate smart road levels for traditional physical road classifications. Near-existing situation (left), and foreseeable future (right).

6.3.2. Functional classification

The Smart Roads Classification can also be combined with the traditional functional classification, which focuses on accessibility and mobility. Cooperative-capable road segments (i.e., smart level AU) should be reserved for major arterials, where accessibility is minimum, traffic volumes are very high and a general speed management would present major benefits (such as lower emissions and congestion, etc.). In addition, Operational Road Sections (ORSs) are likely to be first identified at this kind of infrastructures.

On the other hand, finding ORSs for other local and even some collector roads –where accessibility is maximum– might be very difficult. Probably, these segments would be the latest to be within vehicles' ODDs.

6.3.3. Road users

While the SRC only explicitly considers the presence of connected and/or automated vehicles, the SRC benefits would extend to all users, also including non-motor vehicles and even non-connected ones. Table 32 shows how some users would interact with the road infrastructure. There are five major columns that correspond to the different users. The first two columns correspond to the connectivity (C) and automation (A) capabilities. Passenger cars and heavy vehicles may present one and/or the other, while motorcycles, bicycles/LMVs and pedestrians may only have connectivity.

The red/orange/yellow/green/blue columns correspond to the Humanway, Assistedway, Automatedway, Full Automatedway, and Autonomousway road segments, respectively. Adequate user/road combinations are shown with light color, while the combinations that suffer from some limitations are darkened. A numeric code is provided to indicate which is the limitation (at the bottom of the table).

C	A	Passenger car						Heavy vehicle						Motorcycle						Bicycle/LMV						Pedestrian					
✗	✗				1	2	X				1	2	X				1	2	X				1	2	X				1	2	X
✓	✗		3	3			X		3	3			X		3	3			X		3	3			X		3	3			X
✗	✓		3	4	4		X		3	4	4		X																		
✓	✓		3	3	4				3	3	4																				

C: connectivity. Does the user/vehicle present connectivity capabilities?

A: automation. Does the vehicle present automation capabilities?

The following codes describe the estimated limitations for the interaction between road segment and road user:

1: The road user cannot benefit from all advantages of the road.

2: The road user cannot benefit from all advantages of the road, but the road can detect it and inform other connected users.

3: The user presents connectivity and/or automation capabilities, but the smart level of the road is not able to provide/receive valuable information, and/or generates too many disengagements.

4: Same as 3, but adequacy depends on the SAE level of the vehicle and the LOSAD level of the road segment.

X: Non-connected and/or non-automated vehicles should not be allowed to perform at AU segments, since these would deprecate the performance of other CAVs.

Table 32. Interaction of the users with the different levels of the smart roads.

Depending on the SAE level of CAVs, more detailed interactions exist with the SRLs. These are indicated in the following section.

6.4. Integration with automation levels

Table 33 indicates how the different SAE levels interact with the SRLs. Different colors are used to indicate how this interaction works. SAE level 3 has been divided into two rows, depending on whether the driving automation system presents capabilities to deal with the Minimal Risk Condition or not (these systems may have these possibilities but these are not mandatory). Levels 4 and 5 always must present this feature.

		SRLs				
		1. Humanway	**2. Assistedway**	**3. Automatedway**	**4. Full Automatedway**	**5. Autonomousway**
SAE levels	**1**					
	2 (with ACC+LKA)					
	3 (without MRC)					
	3 (with MRC)					
	4 (MRC included)					
	5 (MRC included)					

Note:

	Adequate
	Allowed, but not especially benefited compared to lower SRLs
	Prohibited

	Allowed, but many ODDs may not be met and therefore human driving might prevail. For SAE level 5, some limitations related the speed may be present.

Table 33. Particular interactions between the different SAE and SRLs. SAE level 3 has been divided into two groups, depending on the availability of MRC capabilities.

6.5. STAKEHOLDERS

The following stakeholders may intervene at the different stages of the Smart Roads Classification application:

- Road Administrations. These own the road infrastructure and are usually in charge of the planning and investment of new facilities.
- Road Operators. They are in charge of the traffic operation and safety management, ensuring adequate conditions for users. There is a high diversity about how responsibilities are shared among RAs and ROs. New models may exist in the future, too.
- OEMs (+TIER1). Automakers and their suppliers are working hard expanding the capabilities of CAVs. These capabilities are evolving fast and would be gradually expanding the ODDs.
- Mobile Network Operators. These stakeholders are the providers of the wireless connectivity that could serve as a basis for C-V2X communications.
- Users. These are the most important agents, since will interact along the road facilities. Tailored information regarding infrastructure and vehicles should be provided for them to ensure a good performance and a fast adoption of CAVs.
- Information Management Providers. Once the Digital Infrastructure shows up in the road environment and connected vehicles become a reality, a lot of information related to performance, road maintenance, etc. will be shared. There is a necessity to collect, process, and share this information with the adequate stakeholders. Information Management Providers covers the stakeholders that will intervene in this process. Other stakeholders such as services providers, trip planners, MaaS providers are part of this group.

6.6. SCENARIOS

The huge uncertainty about the future evolution prevents us from giving a clear situation in the near or distant future. Therefore, a set of plausible scenarios are given. These are presented for different moments, considering some possible situations related to:

- The existence and/or application of a Smart Roads Classification.
- The SAE levels of vehicles.
- Presence of digital infrastructure.
- Data availability.

A plausible situation for all of them is described. Time has not been considered as a variable, given the different moments that these technologies would impact different regions in the world. In the following section –Business models– a more detailed picture of the possible relationships between the stakeholders is given for:

- Planning and designing road infrastructure with the corresponding investment issues.
- Managing the road network.
- Operating along the road network.
- Regulations.
- Design of new vehicles and driving automation systems.
- Test and certification of new vehicles.

Scenarios are characterized by the following dimensions:

- SRC application: yes/no. This field indicates, for each scenario, whether a Smart Roads Classification system exists and can be applied to all or part of the road network. Scenarios without SRC are considered as base conditions. In the latter case, the main contributions of this SRC would be highlighted allowing comparison with scenarios without applying the SRC.
- SAE levels on the market: This indicates which SAE levels exist on the road network (levels 0 to 5). While a future scenario may be free of SAE level 0 and 1 vehicles, these categories are always considered.
- Digital Infrastructure: yes/no. This item indicates whether a Digital Infrastructure exists and has been generalized to all or part of the road network. Considering the current trend, its existence has been always considered for medium- and long-term scenarios. Only for short-term ones its inexistence has been proposed as plausible.
  Note: while being a reality to come, its specifications and detail cannot be discretized and have been considered in the description of the scenarios.
- Existence of data about disengagements and ODD: no / only disengagements / only ODD / disengagements and ODD.
  Note: existence of only ODD data means that manufacturers certify that their vehicles are compatible with certain road characteristics, but no data about disengagements can be retrieved. The ODD with disengagement data is a step further, since disengagements could be used to verify that systems are working properly.

Not all scenarios are possible or probable (e.g., having SAE level 5 vehicles with no human-driven vehicles in a short-term). Other scenarios are very similar, with minimum differences; and finally, there are some scenarios that are less plausible, but can be easily derived from the ones proposed below.

Given the objective of the Special Project –analyzing the feasibility of a Smart Roads Classification–, scenarios without and with a smart classification system are proposed, determining what a certain SRC could provide. Although the SRC may not be the one developed in this Special Project, if the characteristics of a certain road category are close to some of the SRLs proposed in this document, the name of the SRL would be indicated for clarification. Some additional SRLs may be suggested in some cases, as well.

Since there is a huge variability of countries with different situations related to CAVs, it was not considered adequate to set the scenarios as a function of short-, medium-, or long-term. Instead, these are first organized as a function of the available SAE levels on the corresponding road network. The eight proposed scenarios are as follows (see Table 34):

- Existence of SAE level 2-3 vehicles:
  - Scenario A: no existence of a digital infrastructure, no application of an SRC system (reference scenario).
  - Scenario B: no existence of a digital infrastructure, application of an SRC.
  - Scenario C: a primary digital infrastructure exists, application of an SRC.
  - Scenario D: a primary digital infrastructure exists, application of an SRC. Information about automated vehicle disengagements can also be obtained.
- Existence of SAE level 4 vehicles:
  - Scenario E: Natural evolution of the scenario A (no application of an SRC). The digital infrastructure exists.
  - Scenario F: Natural evolution of the scenarios B or C. The digital infrastructure exists and an SRC is applied too.

    - Scenario G: Natural evolution of scenarios B, C or D. In addition to the digital infrastructure and the application of an SRC, information about disengagements can be obtained.
- Existence of SAE level 5 vehicles:
    - Scenario H: Natural evolution of all previous scenarios. An SRC is considered necessary (see the scenario for more details). The digital infrastructure is also necessary, and data about disengagements and/or ODDs are available.

Scenario	Maximum SAE level on the market	SRC application	Digital infrastructure	Data availability
A	3	No	No	No
B	3	Yes	No	No
C	3	Yes	Yes	No
D	3	Yes	Yes	Disengagements
E	4	No	Yes	No
F	4	Yes	Yes	No
G	4	Yes	Yes	Disengagements
H	5	Yes	Yes	Disengagements / ODD

Table 34. Proposed scenarios.

Figure 55 shows how all scenarios are connected. In the short-term, scenarios A, B, C, and D are plausible. When SAE level 4 vehicles become a reality, Scenario E would follow Scenario A –no SRC classification–. Scenario F would follow either Scenario B or C. In this context, it does not seem likely to have SAE level 4 vehicles without a digital infrastructure –at least a simple version–. Scenario G would follow Scenario D. Finally, in the long-term, when SAE level 5 vehicles hit the market, Scenario H would follow Scenarios E, F, or G. In this case, an SRC would be necessary due to the necessity to segregate SAE Level 4+ vehicles from the rest.

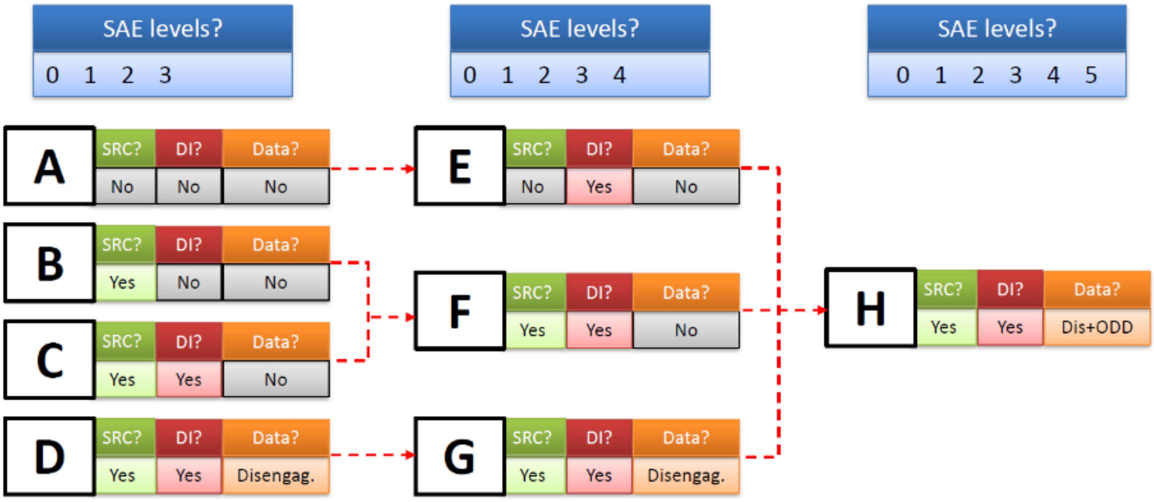

Figure 55. Interaction among the different Scenarios

6.6.1. Scenario A

SAE levels on the market	0	1	2	3	4	5
SRC application	No				Yes	
Digital infrastructure	No				Yes	
Data availability	No		Disengagements		ODD	

This scenario is a near-to-come one, in which an SRC does not exist or is not applied, serving as a reference scenario. Most vehicles do not present automation capabilities (like nowadays), but SAE level 2 vehicles are becoming more and more common. The first SAE level 3 driving automation systems are slowly showing up.

A consensus about how connectivity should be provided to vehicles in a reliable and continuous way has not been reached. This includes the digital infrastructure. In addition, data about automated vehicle disengagements are not available too, as well as explicit data about their ODDs.

This scenario can be considered as an extension of the current situation, where all uncertainties about vehicles, connectivity, and automation performance are still to be resolved. SAE level 2 vehicles would still present disengagements, distributed across the road network. Nowadays, there is still a lot of uncertainty from the user side about the abilities of these systems. Some drivers might expect their vehicle not to release control or performing erratic maneuvers. Although these cases are not frequent, they would become more general and may have a perceptible safety effect when these vehicles are more common.

Like today, their drivers would be able to guess where their vehicles are more or less prone to disengage. As a result, drivers would probably decide to enable the driving automation system on freeways and disable it on medium- and low-end two-lane rural roads.

A critical safety problem may show up in time, as technology evolves and driving automation systems present less disengagements. Drivers might reduce their attention to the driving task and therefore be less ready to retake control when a disengagement occurs. Information and education campaigns would be necessary to familiarize the drivers with these kind of vehicles, as well as to remind the importance of keeping attention to the driving task. ADAS to ensure driver attention might be a good option, too.

The first SAE level 3 vehicles will show up in the market. On the contrary to SAE level 2 vehicles, these ones are able to be in charge of the Driving Dynamic Task (DDT) instead of the driver. However, these vehicles are not completely free of disengagements, although they can foresee them with some time. Thus, if the vehicle foresees an incoming disengagement, it requests the driver to take control (Take Over Request, TOR) with some time in advance, so the human driver can get aware of the environment (including traffic) and resume the DDT.

This being a step forward compared to SAE level 2 vehicles, it is still not clear whether TORs will be provided with sufficient time for the drivers to get aware and resume control. Some stakeholders have claimed that SAE level 3 vehicles may be unsafe unless sufficient time is provided between TORs and disengagements. However, this time depends on (i) the ability of the vehicle to perceive the environment and (ii) the ODD and hardware/software of the vehicle. The environment perceived by the vehicle may be strongly limited by the sight distance, so at higher speeds the time for the driver to react may not be enough.

6.6.2. Scenario B

SAE levels on the market	0	1	2	3	4	5
SRC application	No			Yes		
Digital infrastructure	No			Yes		
Data availability	No		Disengagements		ODD	

This situation is an alternative version to Scenario A, in which a Smart Roads Classification system has been implemented. Given the existence of SAE levels from 0 to 3, two smart types of segments could be identified. The Smart Road Levels would provide valuable information for drivers/connected vehicles such as:

- Road segments that are about to trigger too many disengagements. In these cases, drivers should disable driving assistance. According to the proposed SRC model, these correspond to the Humanway (HU) road segments. This identification should be physical –with signs– so drivers of SAE level 2-3 vehicles should keep manual control, as if the vehicle was not automated. Here, 'are about to' means that this is the expected behavior but there is not direct evidence about disengagements (see below for further clarification).
- Road segments that are about to present good conditions to be driven autonomously. Drivers would be encouraged to enable their driving automation system while keeping attention on the road. According to the proposed SRC model, these correspond to the Assistedway (AS) road segments. This identification should also be with signs, indicating that drivers of SAE level 2-3 vehicles may activate their driving automation systems. However, they should always keep attention on the road. Designating these road segments on freeways could be set as a priority by Road Administrations.

It is important to highlight that the physical signs to identify these road segments are just advisory, informing the drivers about the smart capabilities of the road segment but not forcing them to enable/disable the driving automation system.

Road Administrations and Operators should define which thresholds should be considered to differentiate the road segment levels. Ideally, these should be defined based on the disengagements or ODD information provided by vehicle manufacturers and/or suppliers. Since this information is not available, it is recommended these thresholds to be established upon research that determines which factors and thresholds are more likely to trigger vehicle disengagements. Given the variety across driving automation system technologies, conservative thresholds should be established for posting these advisory signs. An additional categorization of smart roads could be proposed if there are too many differences across the models (e.g., HU, AS, and AS+).

The application of these indications could not be immediate and should be restricted to pilot tests and controlled areas first. Information campaigns should take place at the same moment, to make drivers aware of the capabilities of their SAE level 2-3 vehicles. Pilot tests under controlled conditions should be used before the SRC is extended to the rest of the road network.

The physical indication of the different smart road segment types would help drivers in knowing when and how they are invited to activate their driving automation systems. This would contribute to increase user acceptance in two ways: (i) drivers would experiment less disengagements since the systems would not be enabled on the low-end roads and (ii) globally, drivers would better understand the capacities and limitations of CAVs.

Safety problems may arise at high-end AS road segments with an intermediate HU zone. In this case, physical indication of this HU zone should be provided using a warning –instead of advisory– sign. Additional, complementary signs before that zone with reminders should also be provided.

The thresholds defined by Road Administrations and Operators should be publicly available, and may constitute a goal for vehicle manufacturers and suppliers (e.g., a vehicle compliant with all AS limitations could be tagged as AS-ready or similar). This would work like an ODD although only focusing on basic factors such as road geometry, road markings, etc. It is important to highlight that SAE levels 2-3 cannot ensure disengagement-free driving even within their ODD.

6.6.3. Scenario C

SAE levels on the market	0	1	2	3	4	5
SRC application	No			Yes		
Digital infrastructure	No			Yes		
Data availability	No		Disengagements		ODD	

This scenario is similar to scenario B, adding a digital infrastructure. Since this scenario is focused on the short-term, the digital infrastructure will not probably support cooperative perception or driving.

In addition to the HU and AS smart levels, a new one can be added with special features. Road segments that are likely to present good conditions to be driven autonomously and also present connectivity support should be tagged as Automatedway (AT). Again, a physical sign should indicate this condition to all users, but digital information should be also transmitted to connected and automated vehicles. Variable Message Signs could be used for road segments with no stable connectivity, shifting between AS and AT.

An alternative Smart Road Level may be defined to the road segments that do not present a Digital Infrastructure but have Intelligent Transport System (ITS) features. These road segments already exist and could be identified as AS* (as long as these are not likely to trigger many disengagements, like AS road segments). Moreover, these would probably constitute a primary target for RAs and ROs to deploy the Digital Infrastructure and convert them into real AT road segments.

The connectivity support allows the digital infrastructure to provide valuable information for vehicles about road geometry, traffic, environment, events, etc. SAE level 3 vehicles would result really benefited, since the characteristics of the infrastructure could be transmitted, foreseeing disengagements beyond the line of sight and providing more time between TORs and effective disengagements. Some connected SAE level 2 vehicles could also use this additional information to prevent some disengagements.

6.6.4. Scenario D

SAE levels on the market	0	1	2	3	4	5
SRC application	No			Yes		
Digital infrastructure	No			Yes		
Data availability	No		Disengagements		ODD	

This scenario is similar to scenario C. However, information about disengagements is available, with the following advantages over the previous situation:

- Road Administrations and Operators could see where the most disengagement-triggering zones are. This information could be used to explore the underlying causes of disengagements, proposing measures to speed up CAV compatibility from the physical infrastructure side.
- Given that all data related to disengagements (including location, speed, driving automation system model and version, environment, time, etc.) are available, there is no need for research the triggering causes, just only for processing all data.
- This big database would be updated in real-time, tracking the evolution of disengagements along road segments. This would help Road Administrations and Operators monitor how their different road segments are working, and reactively change some categories.
- The thresholds to differentiate the Smart Road Levels (SRLs) would be much more accurate than for scenario B, since they would be obtained from real data. Again, new possible levels could be proposed if the difference across driving automation systems is too high.

The SRLs that may be applicable in this scenario are the same than for Scenario C (i.e., HU, AS and AT). In both scenarios C and D, it would be desirable to standardize the SRLs, thresholds, and information displayed to drivers across countries. Nevertheless, it would be necessary within the same country.

6.6.5. Scenario E

SAE levels on the market	0	1	2	3	4	5
SRC application	No			Yes		
Digital infrastructure	No			Yes		
Data availability	No		Disengagements		ODD	

This medium-term scenario could be considered as a natural evolution of scenario A, without the application of an SRC, also serving as a reference scenario. SAE level 4 vehicles are hitting the market, with capability to perform without the driver intervention along road segments that meet their ODD.

A digital infrastructure is expected to be available, with some information related to the road infrastructure and traffic conditions. However, the characteristics of the digital infrastructure may differ across the road segments. Therefore, a freeway should present a cutting-edge digital infrastructure while an unpaved road may present a minimal –if any– one.

SAE level 2 vehicles are expected to be the most frequent in the market. Therefore, road users are expected to be familiar with how these systems work. This includes the need to be attentive to the road under all conditions. Private initiatives (like TomTom Roadcheck) are expected to help drivers decide when and how activate their driving automation systems. SAE level 3 vehicles are also expected to be very frequent, as long as these private initiatives can provide information to foresee disengagements and allow the driver to react with sufficient time to TORs.

For the first SAE level 4 vehicles, it would be very important to have clear information about which road segments and/or itineraries can be covered without the driver intervention. This would require detailed information about the road infrastructure and environment, safe harbors, traffic conditions, etc. Again, private initiatives –probably partnered with the vehicle supplier– would be likely to provide this information. It would be of special relevance to have clear indications about where an ODD-compliant road segment starts and ends. This information would be tailored to the driving automation system. If the ODD is influenced by environmental or traffic conditions, this system would benefit from a connection with the digital infrastructure, which would provide it.

Although ODDs are not expected to be officially explicit, the different OEMs would probably run in competition in order to present to the public the most diverse ODDs. This would benefit user acceptance and technology evolution, as well as would help define further explicit and more extensive ODDs.

6.6.6. Scenario F

SAE levels on the market	0	1	2	3	4	5
SRC application	No			Yes		
Digital infrastructure	No			Yes		
Data availability	No		Disengagements		ODD	

This scenario is similar to Scenario E but having a Smart Roads Classification. A digital infrastructure also exists, but probably in a more detailed compared to Scenario C, given the data requirements of some Smart Road Levels.

Similarly to Scenario E, probably most vehicles will rely on infrastructure data provided by private companies like OEMs. This includes HD maps, weather conditions, safe harbors, etc., and would clearly work towards specifying the ODD enter/exit section along the roadway. However, there will be information that should be delivered upon collection from different providers, such as traffic data, events, Variable Message Signs, or performance microdata. The public digital infrastructure should provide this information, and Road Operators should be in charge of it. A Smart Roads Classification could be used to define the level of detail –or availability– of this information.

SAE level 4 vehicles, when combined with V2X capabilities, could develop cooperative driving. This cooperation may go from a simple fine tuning of the speed limit on a road section (e.g., forcing all vehicles to not exceed 100 km/h) to micromanaging speed and maneuvers of vehicles (e.g., to maximize capacity of smart intersections). This requires two contributions from the infrastructure side: (i) strong connectivity capabilities and a harmonized digital infrastructure, and (ii) access control, to clearly indicate which users can access the smart road facility. A Smart Roads Classification would clearly contribute to the latter, physically indicating that a road facility (e.g., dedicated ramp, dedicated lane, etc.) can only be accessed by SAE level 4 vehicles with compatible ODDs. The proposed SRL Autonomousway (AU) would provide this functionality. The rest of the SRLs could be the ones indicated before (i.e., HU, AS and AT), as well as FA for road segments that are fully compatible with all existing driving automation systems.

A Smart Roads Classification would also be useful for Road Administrations and Operators, which could use it to monitor the status of their road network. In combination with other data, such as traffic volume, crashes, etc., investments in smart road segments could be better planned. Changes in safety and traffic operation as a function of the Smart Road Levels could also be tracked.

6.6.7. Scenario G

SAE levels on the market	0	1	2	3	4	5
SRC application	No			Yes		
Digital infrastructure	No			Yes		
Data availability	No		Disengagements		ODD	

This scenario is similar to Scenario F but having public information about disengagements. Again, this has an important effect on road management. These effects should be added to those indicated in Scenario D:

- Sudden increases of the number of disengagements on a certain road section might indicate a problem to solve. Automatic processes could be enabled to temporarily reduce the SRL (using Variable Message Signs and/or digital information, where available).
- Information about disengagements could also be used by Road Administrations and Operators to determine which road segments present less disengagements, allowing a much faster expansion of the locations where SAE level 4 vehicles can perform.

The same SRLs apply than for Scenario F.

6.6.8. Scenario H

SAE levels on the market	0	1	2	3	4	5
SRC application	No			Yes		
Digital infrastructure	No			Yes		
Data availability	No		Disengagements		ODD	

In a long-term scenario, most vehicles will present some kind of automation, including SAE level 5 ones. A robust digital infrastructure will exist and will be available at most locations. Where not available, automated vehicles could perform with some limitations related to cooperative driving, perception, and navigation –but this would not impact autonomy–.

On the contrary to other previous scenarios, an SRC is completely necessary to clearly identify the locations where only SAE level 4+ vehicles are allowed. This would be a requisite for road facilities with high traffic densities and especially for smart intersections.

Vehicle technology would have probably converged to a continuous ODD for SAE level 4 vehicles. As a result, probably most two-lane paved rural roads would be compatible with SAE level 4 vehicles, and ODD would only be limited at urban environments. Therefore, the lower SRLs would only be useful at these environments. Depending on whether lower SAE levels are still admitted on the rural road network, physical signs for these vehicles may be necessary.

Information about the disengagements –if existing– and ODDs should be public and shared in real-time for instant management purposes. Again, the digital infrastructure would collect data from various private providers to facilitate information for smart intersections.

Again, the same SRLs than for Scenario F are applicable.

6.7. Business models

For each one of the scenarios presented above, the relationships between the stakeholders differ. The most important or plausible ones are presented here, highlighting the specific needs and opportunities that may affect the entire ecosystem.

In all cases, the activities and interactions between the stakeholders are described. A final chart for every scenario describes the general situation (Figure 56). This chart is divided in six regions. The top of the chart shows three stages related to the road infrastructure:

- Planning, investment, and design.
- Management.
- Operation.

The bottom part describes three stages for vehicles:

- Design of new vehicles.
- Testing and certification of vehicles.
- Operation.

Since the operation stage of roads and vehicles take place at the same time by the same users, both regions are merged on the right. Separating the two other stages for infrastructure and vehicles, a sixth region related to road authorities and regulations has been placed. Its central location shows its tight connection to all other stages.

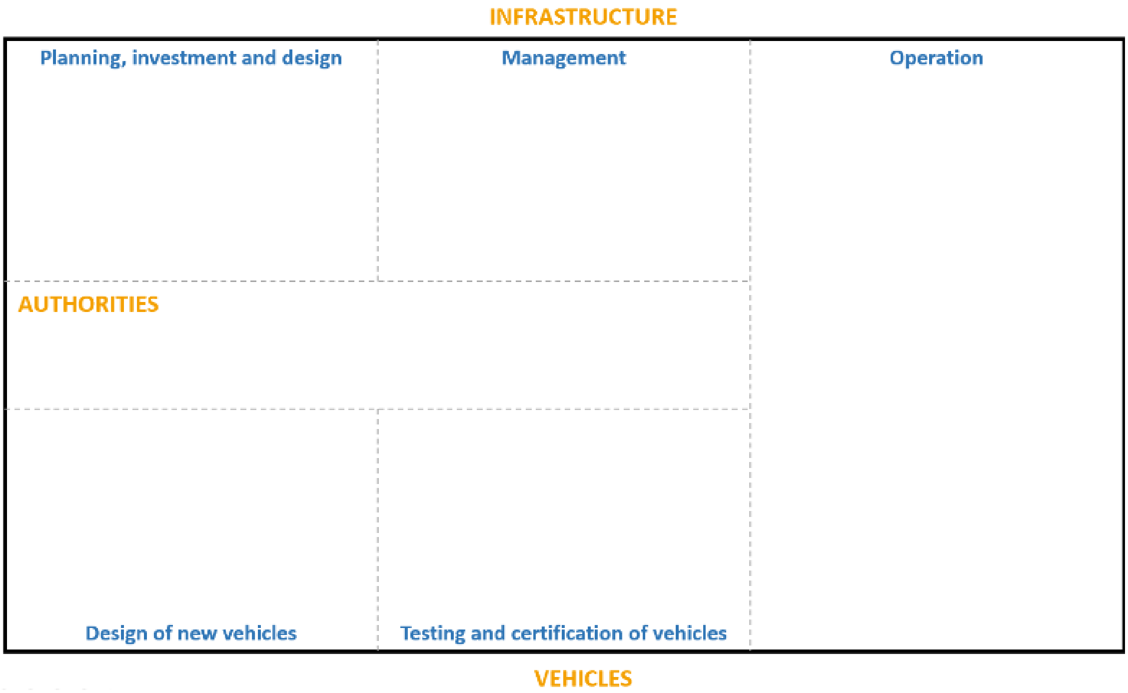

Figure 56. Chart to represent the relationships between stakeholders across the different stages.

In this chart, the different stakeholders are shown as circles with different colors and the following acronyms:

A	Authorities	U	Users
RA	Road Administration	OEM	Original Equipment Manufacturer
RO	Road Operator	IMP	Information Management Provider
MNO	Mobile Network Operator		

All interactions are represented with arrows and some text describing them. The space for these interactions is limited, so these diagrams are to give an insight about the scenario. However, the scenario and the Business model description should always be reviewed as well, to get all information.

6.7.1. Scenario A

Stage: Planning, investment, and design
Road Administrations and Road Operators
Road Administrations and Road Operators should cooperate to determine the impact of the new vehicular functions on crashes and traffic performance. This impact may be positive (lower crash rates and/or higher road capacity) or negative. If the impact is found to be positive, Road Authorities should encourage research to determine which road characteristics and which thresholds have the highest safety impact, when compared to the characteristics of road sections with a negative impact on safety. Road Administrations may use these thresholds to invest on the best benefit/cost ratio actions and design roads or improvements according to them.

Stage: Management of the road network
Road Administrations and Road Operators
Road Administrations and Operators should cooperate to determine whether the new vehicular functions have a real impact on crashes and traffic performance. If the impact is negative, Road Administrations and Operators may encourage drivers not to activate their driving automation systems at certain road segments (e.g., with signs, Variable Message Signs, etc.). If the impact is positive, both should push Authorities to encourage people to buy modern vehicles (e.g., information campaigns, economic incentives, regulations, etc.).

Stage: Operation on the road network
OEMs and TIER1s
Some vehicles may have tailored information about where to activate the driving automation systems. This information would be provided by OEMs or third parties and will not consider any input from the road infrastructure side.
Users
The users will operate SAE level 2-3 vehicles. They would enable or disable the driving automation systems based on their familiarity with their vehicles. Some driving automation systems may have tailored indications provided by OEMs or third parties.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
OEMs should design their vehicles considering information coming from disengagements, but also from global safety pictures provided by Road Administrations (especially if a global reduction in safety is found) and the results from the research campaigns. Strict regulations may come from Authorities if safety is compromised.

Stage: Testing and certification of new vehicles
OEMs and TIER1s
A certification process for a driving automation system does not exist. Instead, there are certification processes for some of the ADAS involved. Although not required, most OEMs would be probably collecting real-world information about the disengagements of their vehicles in order to improve their performance.

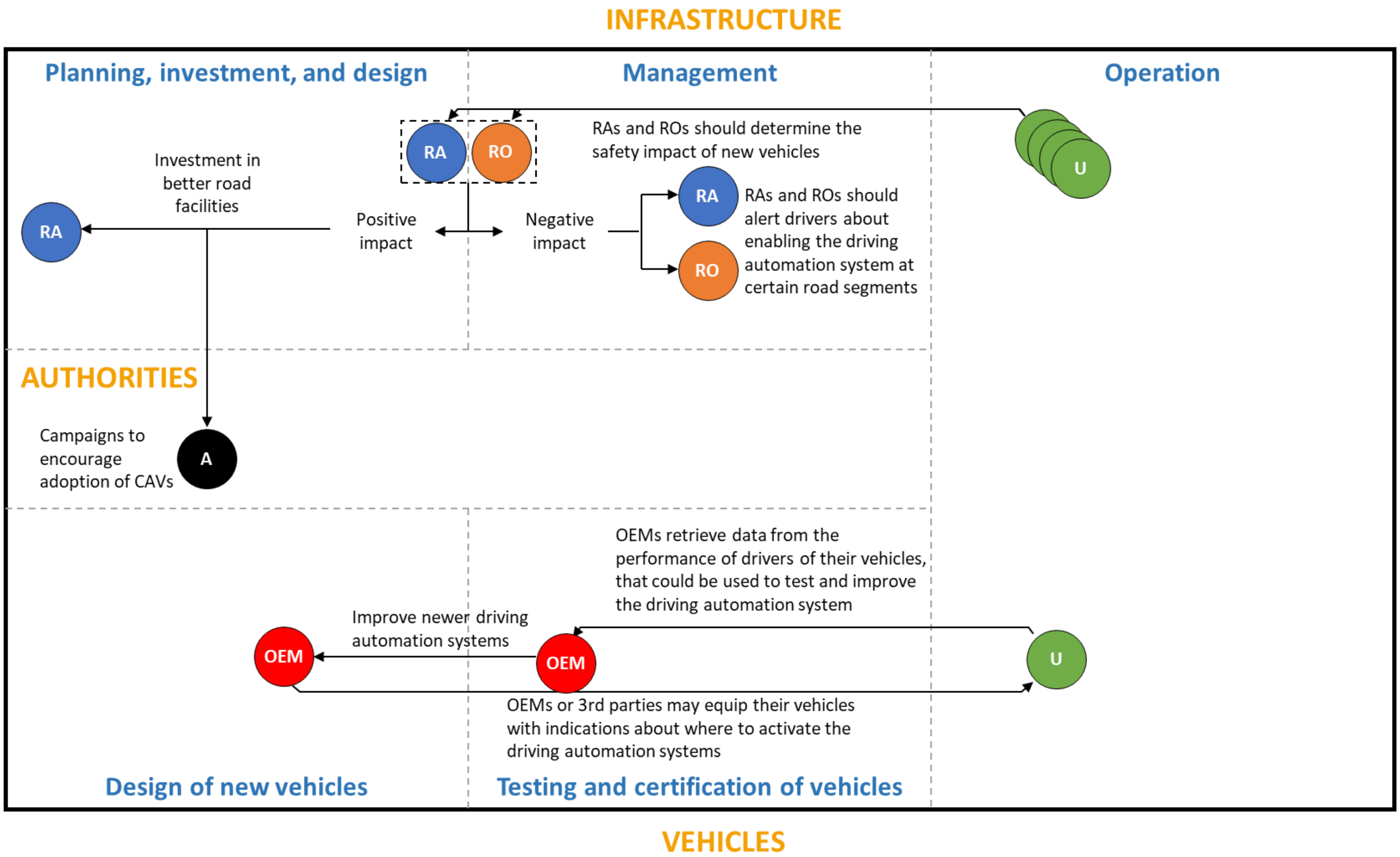

Figure 57. Business model for Scenario A.

6.7.2. Scenario B

Stage: Planning, investment, and design
Road Administrations and Road Operators
Investments on new and existing roads can be designed complying with AS standards, to maximize CAV support. These thresholds should be obtained with research on disengagements with real-world data, in a conservative way. Information about traffic performance and road safety can be used to prioritize actions on the road, starting with freeways.

Stage: Management of the road network
Road Administrations and Road Operators
Based on Road Inventory, RAs and ROs should determine and establish the Smart Road level of their road network –at least the main one– based on static parameters. Based on dynamic factors, Road Operators may temporary change the SRL of a road segment, if Variable Message Signs are present on the road segment. Like for Scenario A, Road Administrations and Operators should cooperate to determine the safety impact of the new vehicles. Authorities would consider this as an input for possible campaigns and regulations.
Authorities
Research campaigns should be established to determine the actual limitations of the existing CAVs in order to define specific thresholds for the SRLs. Considering the safety impact of CAVs, Authorities may develop campaigns, economic incentives, or regulations to encourage the adoption of CAVs. A negative safety impact would require Authorities to regulate certification policies of CAVs (or similar ones).

Stage: Operation on the road network
OEMs and TIER1s
Some vehicles may have tailored information about where to activate the driving automation systems. This information would be provided by OEMs or third parties and will not consider any input from the road infrastructure side.
Users
The roads have vertical signs or Variable Message Signs to provide insight to drivers about where to activate their driving automation systems. Some driving automation systems may have tailored indications provided by OEMs or third parties.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
OEMs can use the thresholds for SRLs as a target for the development of their CAV technologies. Private information about the disengagements of their sold vehicles is expected to be available, too. This could be used for the design of newer CAVs.

Stage: Testing and certification of new vehicles
OEMs and TIER1s
A certification process for a driving automation system does not exist. However, probably OEMs would be likely to present their vehicles compliant with the thresholds for AS road segments (or additional AS+ levels, if existing). Pilot studies should be encouraged to improve road segment capabilities. Although not required, most OEMs would be probably collecting real-world information about the disengagements of their vehicles in order to improve their performance.

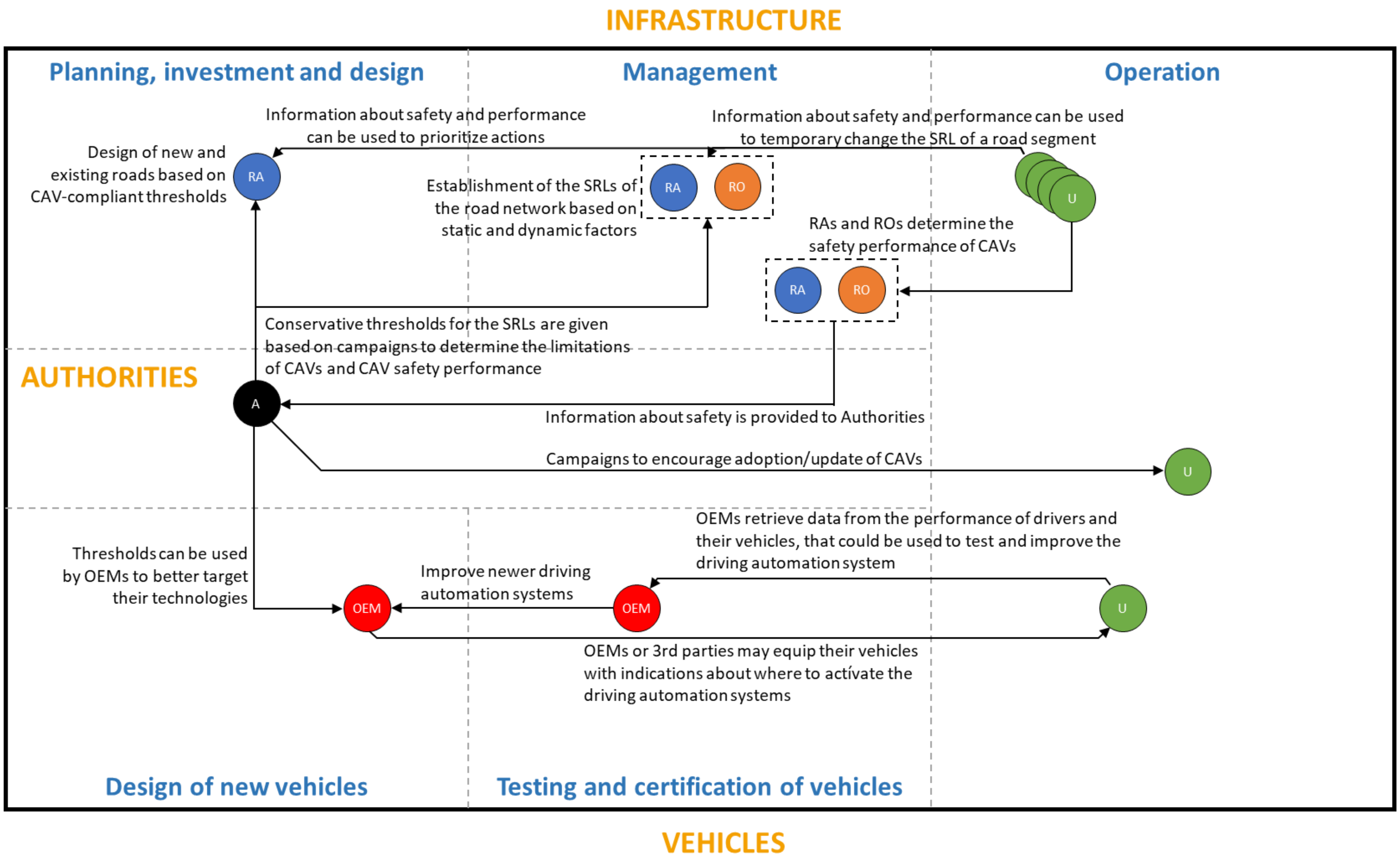

Figure 58. Business model for Scenario B.

6.7.3. Scenario C

Stage: Planning, investment, and design
Road Administrations and Operators
Investments on new and existing roads can be designed complying with AS standards, to maximize CAV support. These thresholds should be obtained with research on disengagements with real-world data, in a conservative way. Information about traffic performance and road safety can be used to prioritize actions on the road, starting with freeways. Information about digital coverage by MNOs should also be considered for AT road segments.
Mobile Network Operators
MNOs should present clear coverage maps. These stakeholders are key to undertake decisions to invest on new AT road segments.

Stage: Management of the road network
Road Administrations and Road Operators
Based on Road Inventory, RAs and ROs should determine and establish the Smart Road Level of their road network –at least the main one– based on static parameters. Based on dynamic factors, Road Operators may temporary change the SRL of a road segment, if VMS are present on the road segment. One of these dynamic factors may be the connectivity coverage of the road segment, provided by the Mobile Network Operator. Like for Scenarios A and B, Road Administrations and Operators should cooperate to determine the safety impact of the new vehicles. Authorities would consider this as an input for possible campaigns and regulations. This information could be directly collected by RAs and ROs, or be delivered via Information Management Providers (IMPs), using the Digital Infrastructure.
Authorities
Research campaigns should be established to determine the actual limitations of the existing CAVs in order to define specific thresholds for the SRLs. Considering the safety impact of CAVs, Authorities may develop campaigns, economic incentives, or regulations to encourage the adoption of CAVs. A negative safety impact would require Authorities to regulate certification policies of CAVs (or similar ones).
Information Management Providers
Using the Digital Infrastructure, these stakeholders may collect information about the traffic performance and road infrastructure state, elaborate it and serve it to RAs and ROs to help them manage the road. In addition, RAs and ROs may use IMPs to send back the information to drivers (on AT road segments).

Stage: Operation on the road network
OEMs and TIER1s
Some vehicles may have tailored information about where to activate the driving automation systems. This information would be provided by OEMs or third parties and may even consider some input from the road infrastructure side.
Mobile Network Operators
MNOs should provide a good connectivity level for all road segments classified as AT. If the coverage is lower, users and RAs/ROs should be informed to reduce the SRL.
Users
HU and AS road segments have vertical signs or Variable Message Signs to provide insight to drivers about where to activate their driving automation systems. Some driving automation systems may have tailored indications provided by OEMs or third parties. AT road segments would have additional information from the digital infrastructure side, preventing some disengagements or helping the shift to manual mode.
Information Management Providers
IMPs may elaborate and tailor the traffic/weather/road information to vehicles, helping to identify ODD-compliant zones and reducing the number of disengagements.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
OEMs can use the thresholds for SRLs as a target for the development of their CAV technologies. Private information about the disengagements of their sold vehicles is expected to be available, too. This could be used for the design of newer CAVs.

Stage: Testing and certification of new vehicles
OEMs and TIER1s
A certification process for a driving automation system does not exist. However, probably OEMs would be likely to present their vehicles compliant with the thresholds for AS and AT road segments (or additional levels, if existing). Pilot studies should be encouraged to improve road segment capabilities. Although not required, most OEMs would be probably collecting real-world information about the disengagements of their vehicles in order to improve their performance.

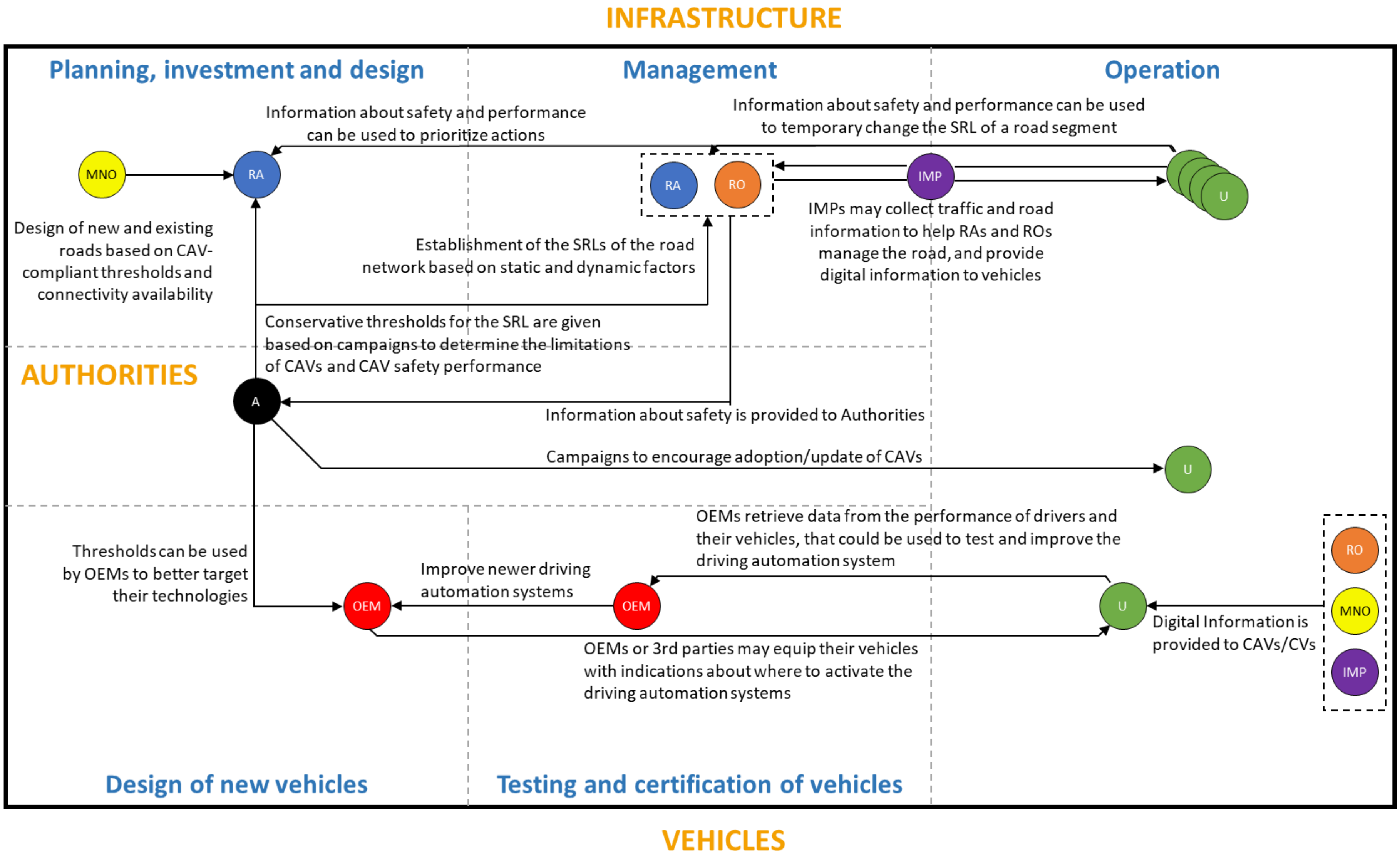

Figure 59. Business model for Scenario C.

6.7.4. Scenario D

Stage: Planning, investment, and design
Road Administrations and Operators
Investments on new and existing roads can be designed complying with AS standards, to maximize CAV support. These thresholds should be obtained from disengagements provided by actual vehicles. Information about traffic performance, road safety, and disengagements can be used to prioritize actions on the road, starting with freeways. Information about digital coverage by MNOs should also be considered for AT road segments.
Mobile Network Operators
MNOs should present clear coverage maps. These stakeholders are key to undertake decisions to invest on new AT road segments.

Stage: Management of the road network
Road Administrations and Operators
Based on Road Inventory, RAs and ROs should determine and establish the Smart Road Level of their road network –at least the main one– based on static parameters. Based on dynamic factors, Road Operators may temporary change the SRL of a road segment, if VMS are present on the road segment. One of these dynamic factors may be the connectivity coverage of the road segment, provided by the Mobile Network Operator. Considering information from disengagements provided by IMPs, Road Administrations and Operators should cooperate to determine which road and environmental conditions trigger vehicle disengagements.
Authorities
Unlike the previous scenarios, public availability of disengagements allows the Authorities to clearly determine the limitations of the existing CAVs. This massive data can be used to generate very accurate thresholds for the SRLs. Considering the safety impact of CAVs, Authorities may develop campaigns, economic incentives, or regulations to encourage the adoption of CAVs. A negative safety impact would require Authorities to regulate certification policies of CAVs (or similar ones).
Information Management Providers
Using the Digital Infrastructure, IMPs should collect information about disengagement, traffic performance, and road infrastructure state, elaborate it and serve it to RAs and ROs to help them manage the road. In addition, RAs and ROs may use IMPs to send back the information to drivers (on AT road segments).

Stage: Operation on the road network
OEMs and TIER1s
Some vehicles may have tailored information about where to activate the driving automation systems. This information would be provided by OEMs or third parties and may even consider some input from the road infrastructure side.
Mobile Network Operators
MNOs should provide a good connectivity level for all road segments classified as AT. If the coverage is low, users and RAs/ROs should be informed to reduce the SRL.
Users
HU and AS road segments have vertical signs or Variable Message Signs to provide insight to drivers about where to activate their driving automation systems. Some driving automation systems may have tailored indications provided by OEMs or third parties. AT road segments would have additional information from the digital infrastructure side, preventing some disengagements or helping the shift to manual mode. Given that thresholds are based on disengagements, it is expected all vehicles to be benefited from more accurate thresholds and recommendations to activate their driving automation systems.
Information Management Providers
IMPs may elaborate and tailor the traffic/weather/road information to vehicles, helping to identify ODD-compliant zones and reducing the number of disengagements.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
OEMs can use the thresholds for SRLs as a target for the development of their CAV technologies. Public information of disengagements could be used for the design of newer CAVs.

Stage: Testing and certification of new vehicles
OEMs and TIER1s
A certification process for a driving automation system does not exist. However, OEMs would be likely to present their vehicles compliant with the thresholds for AS and AT road segments (or additional levels, if existing). Pilot studies should be encouraged to improve road segment capabilities.

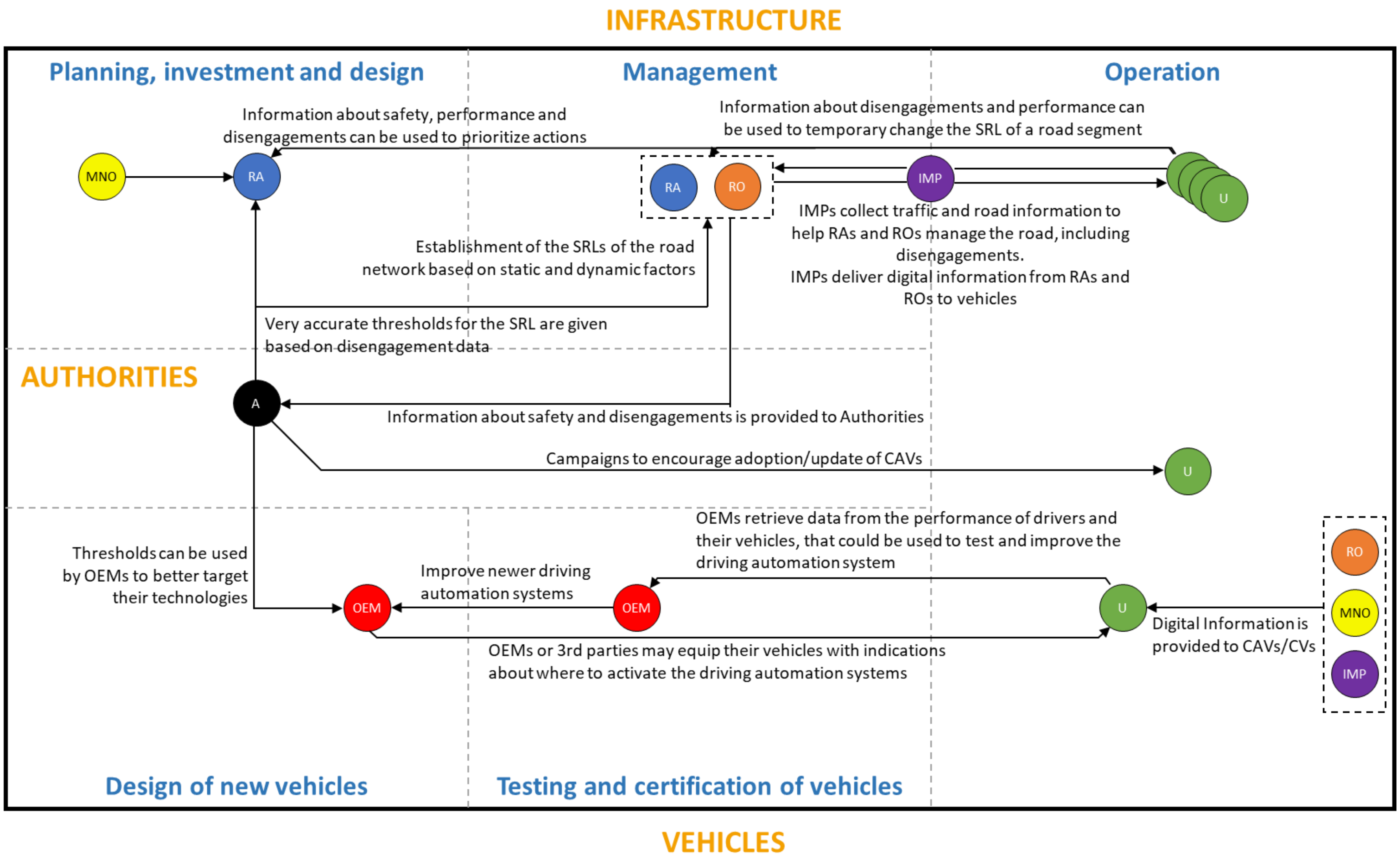

Figure 60. Business model for Scenario D.

6.7.5. Scenario E

Stage: Planning, investment, and design
Road Administrations and Operators
Road Administrations and Operators should cooperate to decide where and how new investments should be applied. Without an SRC system, these investments could be planned based on safety and performance data (like today) obtained from vehicle performance.
Mobile Network Operators
MNOs would be necessary for those road segments required to have Digital Infrastructure services. These services may be very variable and quite specific, given the lack of an SRC system. This contribution may or may not be considered for investments.
Information Management Providers
If Digital Infrastructure Services are going to be provided to vehicles, it would be necessary to establish how the different data are going to be collected and paid.

Stage: Management of the road network
Road Administrations and Operators
RAs and ROs could use the information from user performance and safety to undertake actions on the road management. This information could be directly obtained by their own means or delivered through Information Management Providers. On the other hand, RAs and ROs would produce information for vehicles, that would be delivered with or without intervention of the IMPs. Physical fixed or Variable Message Signs may be used for these indications, as well as digital information (where available).
Authorities
Information about performance would be received from RAs and ROs. Depending on safety and/or performance figures, Authorities may decide to encourage users to buy/update their CAVs, or ask OEMs to change or improve their driving automation systems. Considering the safety impact of CAVs, Authorities may develop campaigns, economic incentives, or regulations to encourage the adoption of CAVs. A negative safety impact would require Authorities to regulate certification policies of CAVs (or similar ones).
Information Management Providers
Using the Digital Infrastructure, these stakeholders should collect information about traffic performance and road infrastructure state, elaborate it and serve it to RAs and ROs to help them manage the road. In addition, RAs and ROs may use IMPs to send back the information to drivers, where the Digital Infrastructure is available. The lack of an SRC system may hinder this application, given that users would not know when they can expect digital information.

Stage: Operation on the road network
OEMs and TIER1s
Some vehicles may have tailored information about where to activate the driving automation systems. This information would be provided by OEMs or third parties and may even consider some input from the road infrastructure side.
Mobile Network Operators
MNOs may or may not present coverage at a certain road segment. Users would presumably not know it beforehand. If this coverage is available, the Digital Infrastructure and additional services may be provided to users and vehicles.
Users
Some users of low SAE level vehicles may have tailored indications provided by OEMs or third parties. Probably, users of higher SAE level vehicles (e.g., SAE level 4) would probably receive specific information about their ODDs provided by their OEMs or third parties. If the Digital Infrastructure is available at the road segment, this information could be used by other drivers to foresee some disengagements. However, users are likely to have great uncertainty about the available digital information.
Information Management Providers
IMPs may elaborate and tailor the traffic/weather/road information to vehicles, helping to identify ODD-compliant zones for SAE level 4 vehicles and reducing the number of disengagements for the rest. Again, there is no certainty about the presence of these services beforehand.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
OEMs should design their vehicles considering private information coming from disengagements, but also from global safety pictures provided by Road Administrations (especially if a global reduction in safety is found). Strict regulations may come from Authorities if safety is compromised.

Stage: Testing and certification of new vehicles
OEMs and TIER1s
Certification processes for CAVs may exist. In this case, Road Authorities should establish the tests and limitations that the models should pass. In addition, most OEMs would be probably collecting real-world information about the disengagements of their vehicles in order to improve their performance.

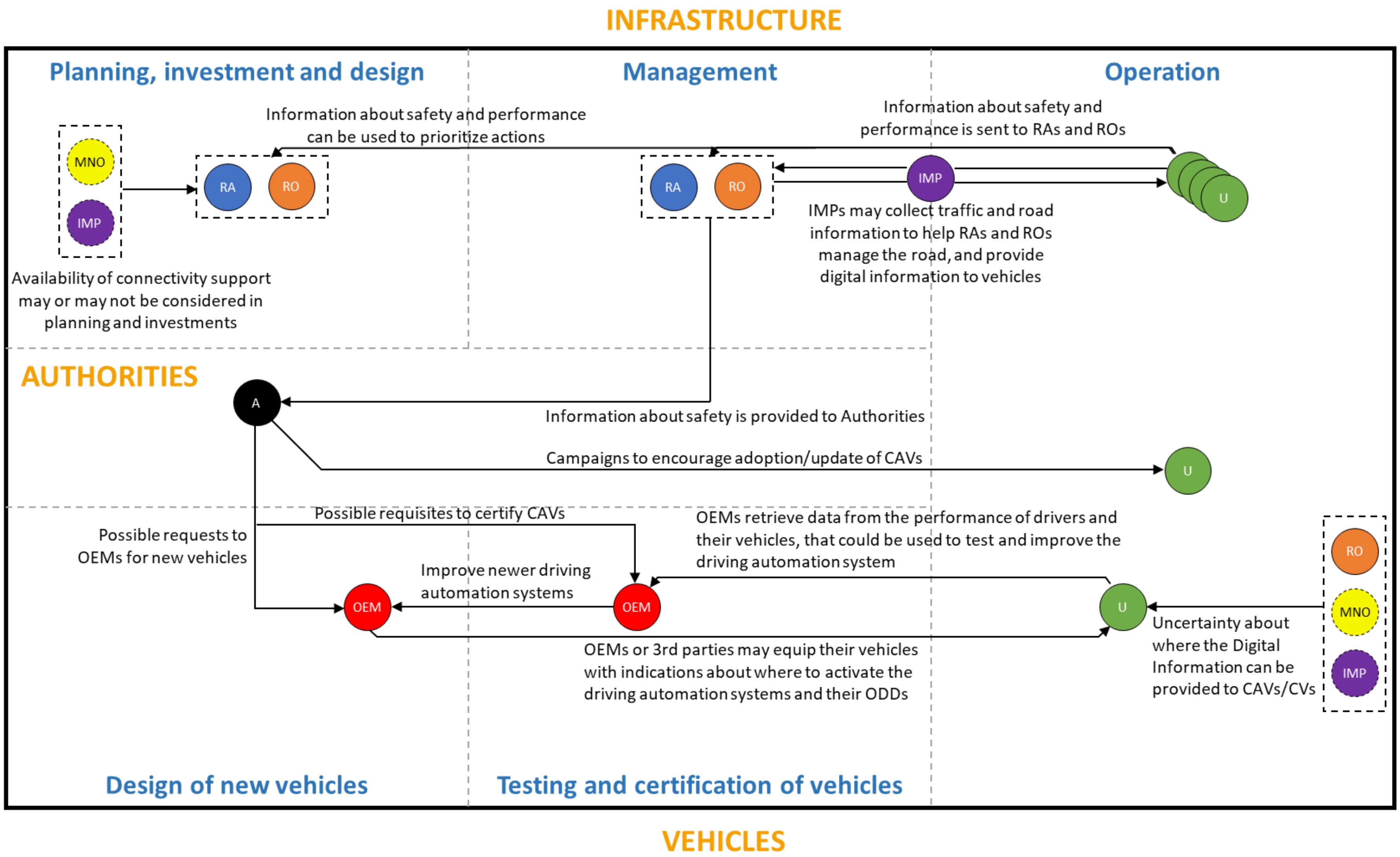

Figure 61. Business model for Scenario E.

6.7.6. Scenario F

Stage: Planning, investment, and design
Road Administrations and Operators
Road Administrations should consider the existing Smart Road Levels to optimize the reimbursement of their investments. Safety and traffic performance data could be considered as input.
Mobile Network Operators
MNOs would be necessary for AT+ road segments, given the need for a Digital Infrastructure. Some variations on the coverage capacity may exist among the levels.
Information Management Providers
For AT+ road segments, Digital Infrastructure Services should be provided to vehicles. It should also be necessary to determine how the different data are going to be collected and paid.

Stage: Management of the road network
Road Administrations and Operators
RAs and ROs could use the information from user performance and safety to undertake actions on the road management. This information could be directly obtained by their own means (HU and AS road segments) or delivered through Information Management Providers (AT+ road segments). On the other hand, RAs and ROs would also produce information for vehicles, that would be delivered with or without intervention of the IMPs. Physical fixed or Variable Message Signs may be used for these indications, as well as digital information. The availability of an SRC makes it clear where and when the different types of information are available.
Authorities
Information about performance would be received from RAs and ROs. Depending on safety and/or performance figures, Authorities may decide to encourage users to buy/update their CAVs or ask OEMs to change or improve their driving automation systems. Considering the safety impact of CAVs, Authorities may develop campaigns, economic incentives, or regulations to encourage the adoption of CAVs. A negative safety impact would require Authorities to regulate certification policies of CAVs (or similar ones). If AU road segments exist, Authorities may want to regulate which vehicles can perform on them, in conjunction with RAs and ROs.
Information Management Providers
On AT+ road segments, using the Digital Infrastructure, IMPs should collect information about traffic performance and road infrastructure state, elaborate it and serve it to RAs and ROs to help them manage the road. In addition, RAs and ROs may use IMPs to send back the information to drivers on the same road segments. Users will always know when these services are available before planning their routes.

Stage: Operation on the road network
OEMs and TIER1s
Most vehicles will have tailored information about where to activate the driving automation systems. This information may be provided by OEMs or determined upon the Digital Infrastructure on AT+ road segments.
Mobile Network Operators
MNOs should present coverage at AT+ road segments. Different MNOs may compete among them to offer their services. Different market shares or agreements should be established to make sure data coverage is not lost.
Users
The users of lower-end SAE level vehicles may have tailored indications provided by OEMs or third parties about where to enable/disable their driving automation systems. This information would be available everywhere. For AT+ road segments, the users of higher SAE level vehicles (e.g., SAE level 4) would be able to use information from the Digital Infrastructure to compare it to their ODDs. Users would be able to plan their routes using mobile coverage filters.
Information Management Providers
The clear identification of the road segments that present connectivity capabilities could enable many information-related services to appear and operate on these road segments. Some of them may elaborate and tailor the traffic/weather/road information to vehicles, helping to identify ODD-compliant zones for SAE level 4 vehicles and reducing the number of disengagements for the rest.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
OEMs should design their vehicles considering private information coming from disengagements, but also from global safety pictures provided by Road Administrations (especially if a global reduction in safety is found). Strict regulations may come from Authorities if safety is compromised.

Stage: Testing and certification of new vehicles
OEMs and TIER1s
Certification processes for CAVs may exist. In this case, Road Authorities should establish the tests and limitations that the models should pass. In addition, most OEMs would be probably collecting real-world information about the disengagements of their vehicles in order to improve their performance.

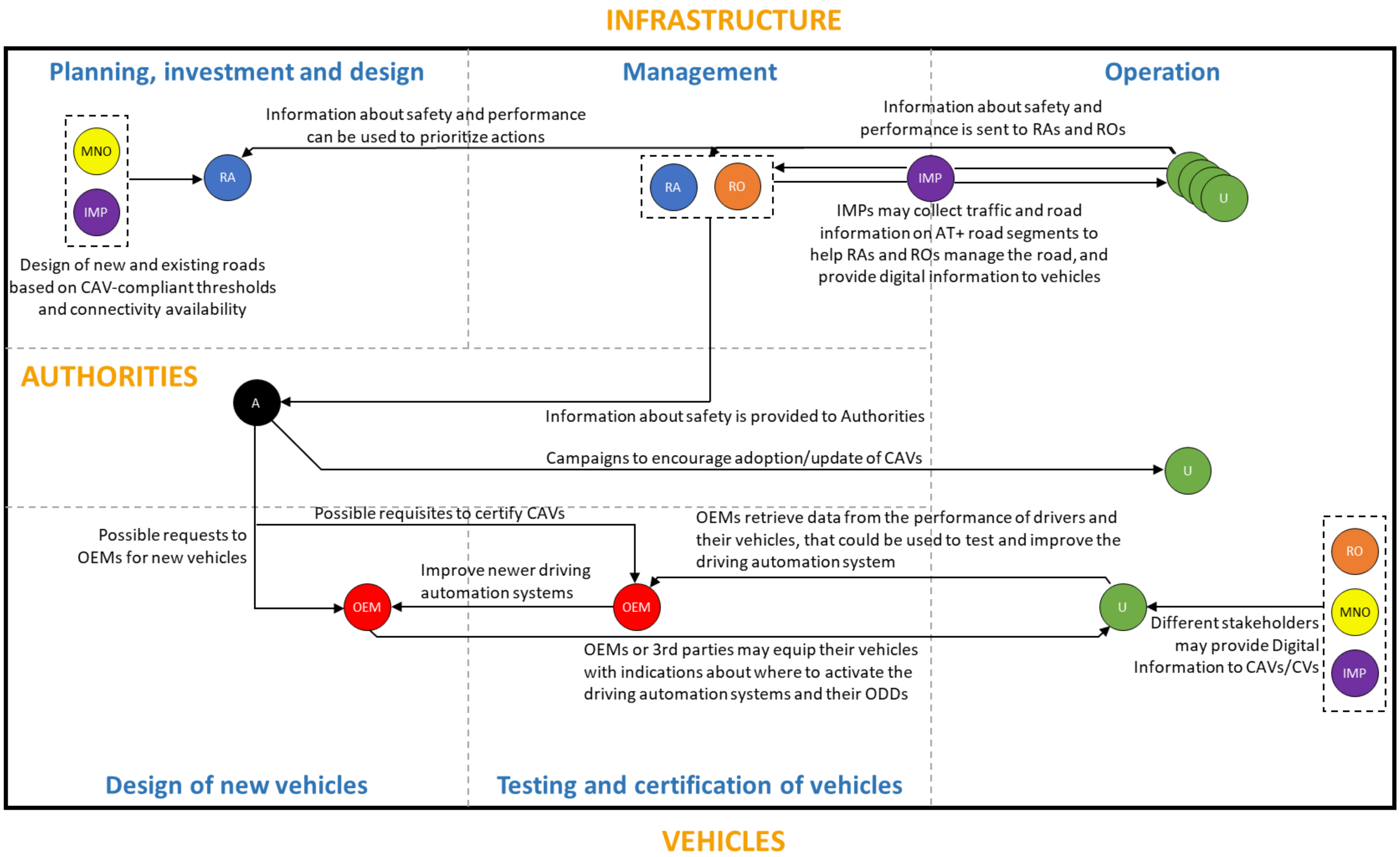

Figure 62. Business model for Scenario F.

6.7.7. Scenario G

Stage: Planning, investment, and design
Road Administrations and Operators
Road Administrations should consider the existing Smart Road Levels to optimize the reimbursement of their investments. Safety and traffic performance data could be considered as input.
Mobile Network Operators
MNOs would be necessary for AT+ road segments, given the need for a Digital Infrastructure. Some variations on the coverage capacity may exist among the levels.
Information Management Providers
For AT+ road segments, Digital Infrastructure Services should be provided to vehicles. It should also be necessary to determine how the different data are going to be collected and paid.

Stage: Management of the road network
Road Administrations and Operators
RAs and ROs could use the information from user performance, safety, and disengagements to undertake actions on the smart road management. This information could be directly obtained by their own means (HU and AS road segments) or delivered through Information Management Providers (AT+ road segments). Sudden disengagements could be used to reduce the SRL of a road segment. In addition, the public availability of disengagements may help Road Authorities and Operators to determine in a very accurate way the thresholds for the different SRL. On the other hand, RAs and ROs would also produce information for vehicles, that would be delivered with or without intervention of the IMPs. Physical fixed or Variable Message Signs may be used for these indications, as well as digital information. The availability of an SRC makes it clear where and when the different types of information are available.
Authorities
Information about performance would be received from RAs and ROs. Depending on safety and/or performance figures, Authorities may decide to encourage users to buy/update their CAVs or ask OEMs to change or improve their driving automation systems. Considering the safety impact of CAVs, Authorities may develop campaigns, economic incentives, or regulations to encourage the adoption of CAVs. A negative safety impact would require Authorities to regulate certification policies of CAVs (or similar ones). If AU road segments exist, Authorities may want to regulate which vehicles can perform on them, in conjunction with RAs and ROs.
Information Management Providers
On AT+ road segments, using the Digital Infrastructure, IMPs should collect information about traffic performance and road infrastructure state, elaborate it and serve it to RAs and ROs to help them manage the road. In addition, RAs and ROs may use IMPs to send back the information to drivers on the same road segments. Users will always know when these services are available before planning their routes.

Stage: Operation on the road network
OEMs and TIER1s
Most vehicles will have tailored information about where to activate the driving automation systems. This information may be provided by OEMs or determined upon the Digital Infrastructure on AT+ road segments.
Mobile Network Operators
MNOs should present coverage at AT+ road segments. Different MNOs may compete among them to offer their services. Different market shares or agreements should be established to make sure data coverage is not lost.
Users
The users of lower-end SAE level vehicles may have tailored indications provided by OEMs or third parties about where to enable/disable their driving automation systems. This information would be available everywhere. For AT+ road segments, the users of higher SAE level vehicles (e.g., SAE level 4) would be able to use information from the Digital Infrastructure to compare it to their ODDs. Users would be able to plan their routes using mobile coverage filters.
Information Management Providers
The clear identification of the road segments that present connectivity capabilities could enable many information-related services to appear and operate on these road segments. Some of them may elaborate and tailor the traffic/weather/road information to vehicles, helping to identify ODD-compliant zones for SAE level 4 vehicles and reducing the number of disengagements for the rest.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
OEMs should design their vehicles considering information coming from disengagements, but also from global safety pictures provided by Road Administrations (especially if a global reduction in safety is found). Strict regulations may come from Authorities if safety is compromised.

Stage: Testing and certification of new vehicles
Authorities
Authorities may ask OEMs to perform tests in real-world environments. Since data about disengagements are publicly available, this process would be very fast and transparent.
OEMs and TIER1s
Certification processes for CAVs may exist. In this case, Road Authorities should establish the tests and limitations that the models should pass. In addition, most OEMs would be probably collecting real-world information about the disengagements of their vehicles in order to improve their performance.

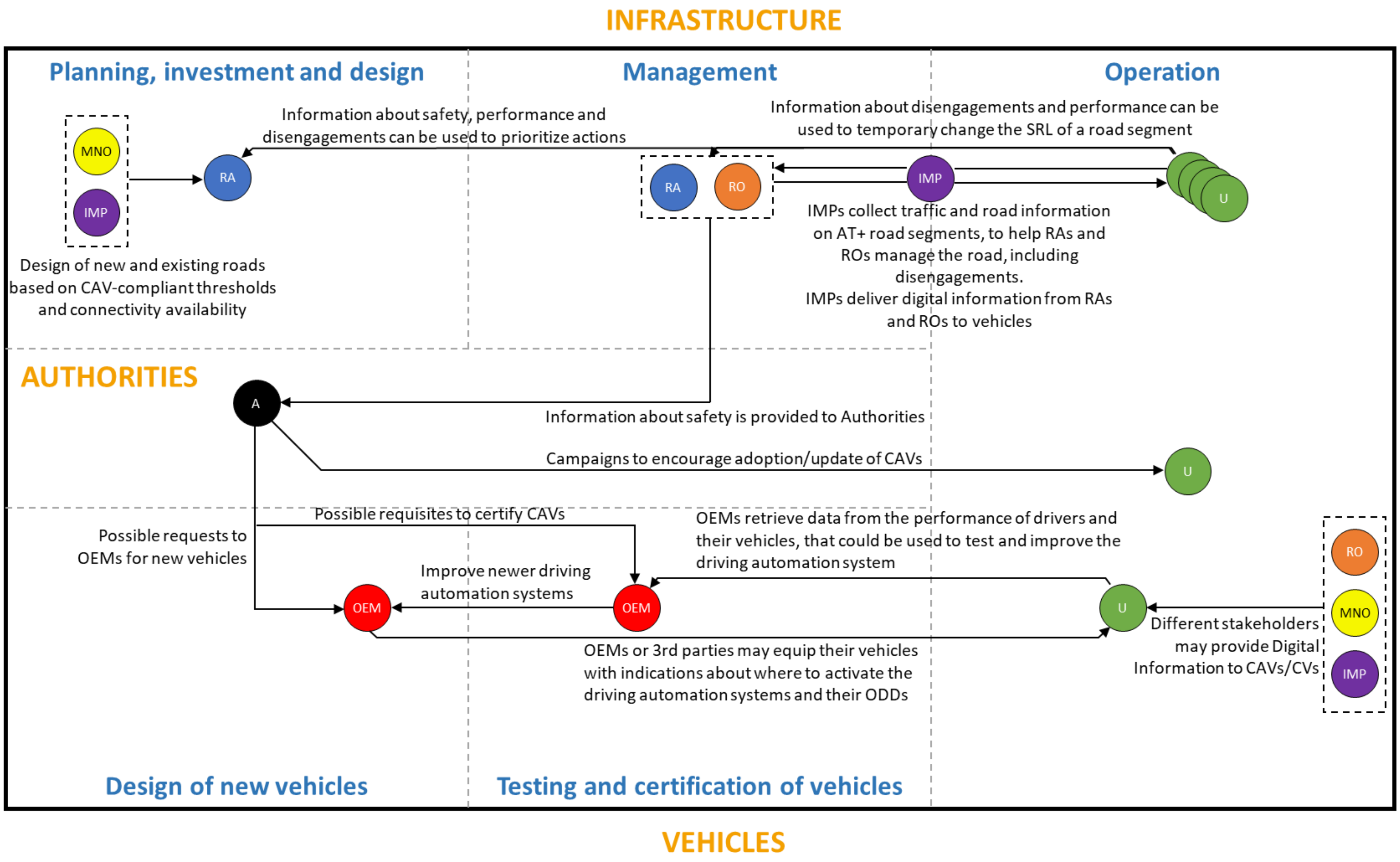

Figure 63. Business model for Scenario G.

6.7.8. Scenario H

Stage: Planning, investment, and design
Road Administrations and Operators
Road Administrations should consider the existing Smart Road Levels to optimize the reimbursement of their investments. Most CAVs would be fully compatible with rural roads (general ODD), letting the ODD limitations mainly to urban environments.
Mobile Network Operators
MNOs would be necessary for AT+ road segments, given the need for a Digital Infrastructure. It is expected that most local road segments are classified as AT, while main segments are FA or AU.
Information Management Providers
For AT+ road segments, Digital Infrastructure Services should be provided to vehicles. These services are expected to vary between AT, FA, and AU road segments. It should also be necessary to determine how the different data are going to be collected and paid.

Stage: Management of the road network
Road Administrations and Operators
RAs and ROs should use the information from user performance, safety, and disengagements to undertake actions on the road management. Since that most road segments would be AT+, this information would be probably delivered through Information Management Providers. Disengagements/Take Over Requests are expected to be minimum, but these could be used to reduce the SRL of a road segment or temporarily warn other drivers about a road capacity limitation. RAs and ROs would produce information for vehicles, that would be delivered through IMPs. Physical (where needed) and digital information would be provided.
Authorities
Information about performance would be received from RAs and ROs. The technological evolution of CAVs is expected to stagnate. Therefore, the certification processes are expected to be well established and with no major need to change. Authorities should regulate which vehicles can perform on AU road segments, in conjunction with RAs and ROs. Since CAVs are mature, before being allowed to circulate, authorities should define the safety requirements a CAV must fit, to run –or not– in a degraded mode, regardless the technology they incorporate.
Information Management Providers
On AT+ road segments, using the Digital Infrastructure, IMPs should collect information about traffic performance and road infrastructure state, elaborate it and serve it to RAs and ROs to help them manage the road. In addition, RAs and ROs may use IMPs to send back the information to drivers on the same road segments. Users will always know when these services are available before planning their routes.

Stage: Operation on the road network
OEMs and TIER1s
Most vehicles will have tailored information about where to activate the driving automation systems. This information may be provided by OEMs or determined upon the Digital Infrastructure on AT+ road segments.
Mobile Network Operators
Coverage would probably be present along all road segments. Different MNOs may compete among them to offer their services. Different market shares or agreements should be established to make sure data coverage are not lost.
Users
The Digital Infrastructure would provide valuable information to all vehicles, so they can check whether they meet the ODD, and under which conditions. Users would be able to plan their routes using mobile coverage filters.
Information Management Providers
The high connectivity and data-based services would foster the existence of many Information Management Providers. In addition to basic services such as traffic/weather/road information, advanced computing services could be used to manage traffic, maintenance, etc.

Stage: Design of new vehicles and driving automation systems
OEMs and TIER1s
Vehicles are expected to be almost ODD-free at rural environments. Therefore, information about disengagements would not be extremely valuable for OEMs. New vehicular developments would be probably oriented towards comfort, efficiency, etc.

Stage: Testing and certification of new vehicles
Authorities
Like previous scenarios, Authorities may ask OEMs to perform tests in real-world environments. Since data about disengagements are publicly available, this process would be very fast and transparent.
OEMs and TIER1s
Certification processes for CAVs would exist. Road Authorities should establish the tests and limitations that the models should pass.

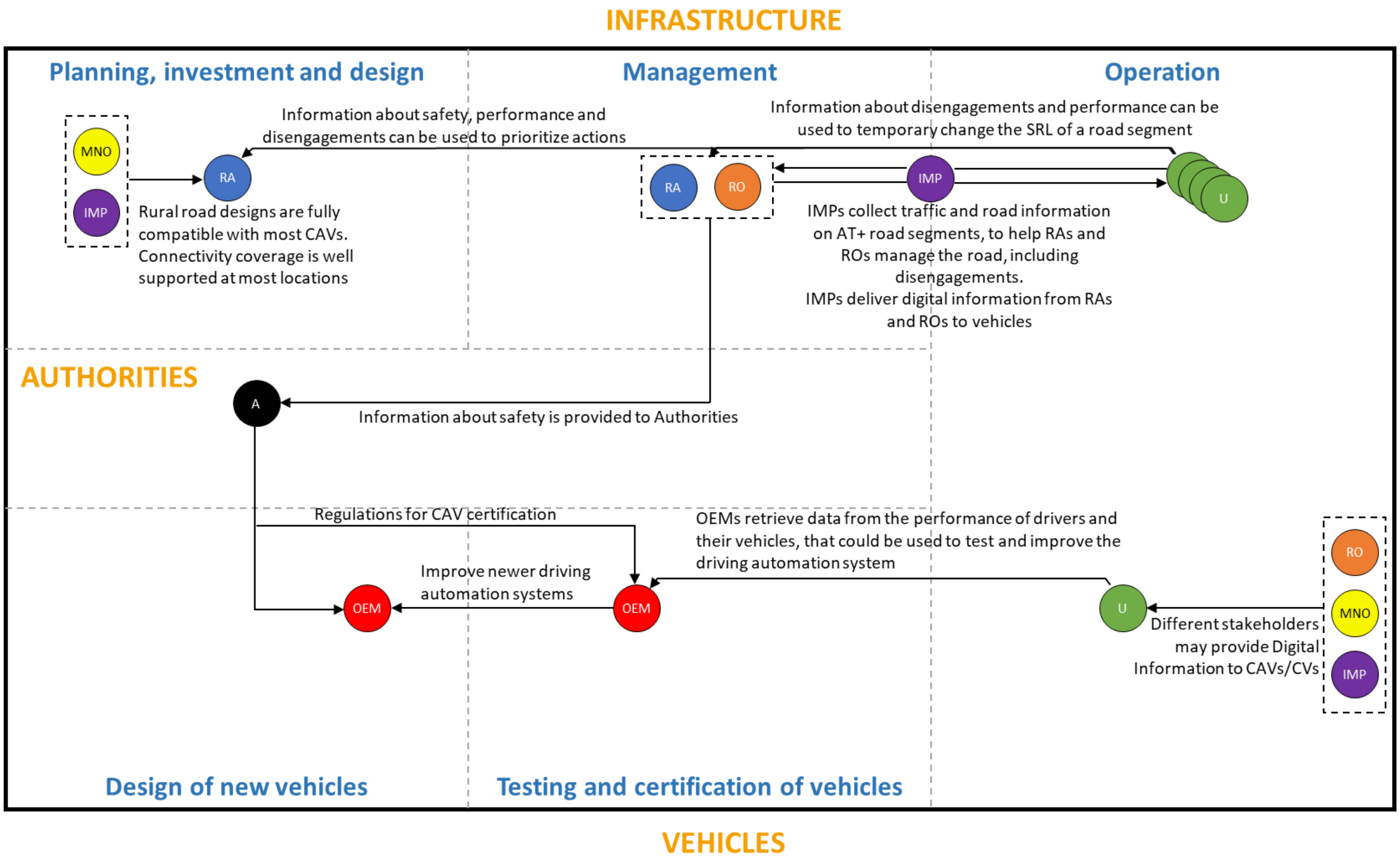

Figure 64. Business model for Scenario H.

6.7.9. Business Evaluation

Scenarios that require the deployment of digital infrastructure (C to H) to facilitate connectivity involve significant investments and maintenance costs. It is necessary to consider, for all stakeholders, the various economic and financial alternatives to make the new smart road system viable.

Table 35 shows for each of the stakeholders and alternatives, the various ways to accommodate the investments, the payments, or costs during the provision of the service, and the possible options to obtain revenues.

The RAs may make the entire investment in the deployment of the digital infrastructure –like they have done so far to facilitate ITS–. An alternative is to modify existing concession contracts or make new concessions with ROs and/or MNOs. There could be several sources of revenue, depending on the stakeholder:

- Providing physical and digital infrastructure and traffic data.
- A subscription fee for the connectivity service and a temporary service fee.
- An additional road tax for the purchase of CAVs or CVs.
- Increased toll rate or pay-per-use fee.
- Increasing the number of 5G clients with a higher subscription.
- Receiving personalized information from a provider.
- For users providing data from their vehicles on road conditions and disengagements.

Stakeholder	Alternative	Investment	Payment	Income
RA		100% DI (as ITS deployment)	Maintenance by RA	Providing data from PI/DI and traffic; registration fee, road tax, CAVs/CVs connectivity service fee
RO	Existing Road Concession Agreement (BOT)	100% DI by RA (as ITS deployment)	Maintenance by RA	Providing data from PI/DI and traffic; registration fee, road tax, CAVs/CVs connectivity service fee
		Shared with RA through upgraded agreement	Maintenance by RO	Providing data from PI/DI and traffic; longer period; higher user toll rate due to CAVs/CVs connectivity service…
	Existing Road Management Concession Agreement	100% DI by RA (as ITS deployment)	Maintenance by RA	Providing data from PI/DI and traffic; registration fee, road tax, CAVs/CVs connectivity service fee
		Shared with RA through upgraded agreement	Maintenance by RO	Providing data from PI/DI and traffic; longer period; higher user fee due to CAVs/CVs connectivity service…
	New Road Concession Agreement (BOT)	100% DI by RA	Maintenance by RO and possibly RA	Providing data from PI/DI and traffic; registration fee, road tax, CAVs/CVs connectivity service fee
		Shared with RA through PPP (% to be determined)	Maintenance by RO	Providing data from PI/DI and traffic; higher user toll rate due to CAVs/CVs connectivity service…
	New Road Management Concession Agreement	100% DI by RA	Maintenance by RO and possibly RA	Providing data from PI/DI and traffic; registration fee, road tax, CAVs/CVs connectivity service fee
		Shared with RA through PPP (% to be determined)	Maintenance by RO	Providing data from PI/DI and traffic; higher user fee due to CAVs/CVs connectivity service…
MNOs	Serving to enough surrounding population non-V2X services	Deployment 100% by MNO (cellular infrastructure along the road)	Maintenance by MNOs	Much higher number of 5G clients and higher fee (subscription). Possible income for prioritization of V2X traffic
	Not enough surrounding population	Shared with RA/RO through PPP (% to be determined). To be added to the above DI investments by RA/RO	Maintenance by MNOs	Higher number of 5G clients and higher fee (subscription). Only C-V2X users. Possible income for prioritization of V2X traffic
IMPs			Data from PI/DI and traffic management	Users (drivers/CAVs) may pay a fee (subscription) for personalized information availability (there may be more than one provider)

USERs	CAV owners may be required to pay additional taxes or have incentives for buying CAVs.	May pay a higher toll rate or fee. May pay a fee for personalized information availability	There may be income for providing road condition and disengagement information

Table 35. Business Evaluation for all stakeholders.

A brief techno-economic study is presented to provide a more solid insight about the investment cost. It is reasonable to conjecture that, when deploying the telecommunication infrastructure needed for the support of Connected and Automated Vehicles (CAVs), each of the proposed Smart Road Level implies different investment intensities (in terms of cost and time).

Regarding time, this Project assumes that the investment timeframes for the potential rollouts are correlated to the upper bound predictions from MANTRA project [143]. Table 36 shows for vehicle fleet penetration of automated vehicles (at least SAE level 3) for cars, heavy goods vehicles, and taxis (the figures for 2025 have been interpolated from estimations on new cars sold also in [143]). From these values it may be deduced that: (i) 2021-2025 will be the period for network pilots and preliminary support of simple services, (ii) 2026-2030 will bring with it an increase on network deployment to support more advanced services (matching the early market assumptions of 2030), and (iii) this will pave the way to the progressive mass adoption expected from 2031 to 2040.

	Fleet penetration (%)		
Fleet	**2025**	**2030**	**2040**
Cars	0.30	4.7	38.6
Heavy goods vehicles	0.20	3.2	42.6
Taxis	0.50	8.2	70.8

Table 36. Vehicle fleet penetrations [144].

Regarding cost, this study distinguishes between the capital expense (CAPEX) –i.e., the cost of deploying the telecommunication infrastructure– and the operating expenses (OPEX) –i.e., the ongoing costs of running the network–. Note that more sophisticated Smart Road Levels imply costlier rollouts to satisfy the capabilities of CAVs with the adequate level of service. Table 37 and Table 38 show the average CAPEX and OPEX yearly cost estimations per kilometer of road considering a typical road segment (freeways/motorways with an average coverage complexity) for the 2021-2025 and 2026-2030 periods, respectively, depending on how ready to host CAVs is the specific Smart Road Level.

Smart Road Level	Yearly digital infrastructure cost estimation (€/km), 2021-2025		
	Roadside	***Cellular***	***Hybrid (roadside + cellular)***
Assistedway	CAPEX, w/ cabling: 3,500 €/km w/o cabling: 1,800 €/km OPEX: 900 €/km	CAPEX, w/ cabling: 2,300 €/km w/o cabling: 1,900 €/km OPEX: 350 €/km	CAPEX, w/ cabling: 2,100 €/km w/o cabling: 1,600 €/km OPEX: 325 €/km
Automatedway	CAPEX, w/ cabling: 5,500 €/km w/o cabling: 2,200 €/km OPEX: 1,200 €/km	CAPEX, w/ cabling: 2,800 €/km w/o cabling: 2,400 €/km OPEX: 400 €/km	CAPEX, w/ cabling: 2,500 €/km w/o cabling: 2,000 €/km OPEX: 350 €/km
Full Automatedway	CAPEX, w/ cabling: 8,800 €/km w/o cabling: 2,400 €/km OPEX: 1,500 €/km	CAPEX, w/ cabling: 3,500 €/km w/o cabling: 2,800 €/km OPEX: 500 €/km	CAPEX, w/ cabling: 3,200 €/km w/o cabling: 2,100 €/km OPEX: 450 €/km
Autonomousway	CAPEX, w/ cabling: 11,600 €/km w/o cabling: 3,200 €/km OPEX: 1,950 €/km	CAPEX, w/ cabling: 4,300 €/km w/o cabling: 3,700 €/km OPEX: 600 €/km	CAPEX, w/ cabling: 3,500 €/km w/o cabling: 3,000 €/km OPEX: 500 €/km

Table 37. 2021-2025 CAPEX/OPEX estimations to achieve each Smart Road Level.

Smart Road Level	Yearly digital infrastructure cost estimation (€/km), 2026-2030		
	Roadside	***Cellular***	***Hybrid (roadside + cellular)***
Assistedway	CAPEX, w/ cabling: 7,500 €/km w/o cabling: 7,000 €/km OPEX: 3,300 €/km	CAPEX, w/ cabling: 3,800 €/km w/o cabling: 3,500 €/km OPEX: 2,300 €/km	CAPEX, w/ cabling: 3,600 €/km w/o cabling: 3,300 €/km OPEX: 2,200 €/km
Automatedway	CAPEX, w/ cabling: 9,000 €/km w/o cabling: 8,500 €/km OPEX: 3,700 €/km	CAPEX, w/ cabling: 4,200 €/km w/o cabling: 3,900 €/km OPEX: 2,500 €/km	CAPEX, w/ cabling: 4,000 €/km w/o cabling: 3,500 €/km OPEX: 2,300 €/km
Full Automatedway	CAPEX, w/ cabling: 14,500 €/km w/o cabling: 9,000 €/km OPEX: 4,000 €/km	CAPEX, w/ cabling: 5,000 €/km w/o cabling: 4,500 €/km OPEX: 2,800 €/km	CAPEX, w/ cabling: 4,700 €/km w/o cabling: 3,900 €/km OPEX: 2,500 €/km
Autonomousway	CAPEX, w/ cabling: 19,200 €/km w/o cabling: 11,900 €/km OPEX: 5,300 €/km	CAPEX, w/ cabling: 6,200 €/km w/o cabling: 5,600 €/km OPEX: 3,600 €/km	CAPEX, w/ cabling: 5,800 €/km w/o cabling: 4,800 €/km OPEX: 2,800 €/km

Table 38. 2026-2030 CAPEX/OPEX estimations to achieve each Smart Road Level.

Table 37 and Table 38 consider the cases where only roadside infrastructure, only cellular, and hybrid (roadside plus cellular) infrastructure are deployed. As shown, when the hybrid approach is taken, savings are expected because a significant part of the road segment is covered with cellular and resorting to road infrastructure is reserved for those sections that require critical coverage (e.g., tunnels). Roadside CAPEX calculations account for the cost of purchasing the Roadside Units (RSUs) hardware. Cellular CAPEX calculations include the cost of cellular sites (tower plus antenna) and backhaul. For the CAPEX, the need of rolling cable (or not) is also distinguished. In both options, OPEX calculations derive from energy consumed and diverse maintenance costs. The deployment addressed by Table 37 in 2021-2025 supports the following basic vehicle-to-everything (V2X) services inspired by proposals by the 5G Automotive Association (5GAA) [144] [145] [146] as well as their corresponding Key Performance Indicators: local hazard and traffic information, hazard information collection and sharing for automated vehicles, emergency electronic brake light, and left turn assist. The Autonomousway values have been lightened given that SAE levels 4-5 vehicles are not expected in such a short-term. Table 38 tries to support the following, more advanced services with stringent throughput and latency requirements for adoption in 2026-2030: high-definition map collection and sharing for automated vehicles, vulnerable road user, collective awareness, informative sensor sharing, tele-operated driving, group start, sensor sharing for automated vehicles, cooperative maneuvers, and high-definition sensor sharing for automated vehicles [144] [145] [146]. Because of the strict end-to-end delay demands of the previously mentioned services, Table 38 assumes that

Mobile Edge Computing (MEC) is deployed at the edge of the network (and it includes the corresponding CAPEX/OPEX of hardware, installation, and maintenance of such facilities).

In each table, an Assistedway road segment is covered with either classical or 802.11p RSUs, or 2G/3G/4G cell sites; Automatedway level marks the introduction of 5G infrastructure for elemental coverage of the road; for Full Automatedway level the 5G deployment on the road tries to trade off coverage and cost (sometimes leaving minimized coverage holes); and at Autonomousway level the entity performing the deployment spares no expense in covering the road perfectly. Finally, note that by their very limited nature, all deployments for Assistedway level (pure 4G) and most of the deployments for Automatedway (only incipient 5G) will not be able to fulfill decently the rigorous KPIs expected from the services deployed in the 2026-2030 timeframe. These costs represent an upper threshold. In many cases, simpler investments –like the ones for the previous period of time– could provide enough support for lower-end SAE level vehicles.

6.8. Use Cases

This section consists of the description of diverse use cases concerning different scenarios (B, D, G, and H). The main objective is to facilitate all stakeholders the application of the SRC under diverse situations that could be given in any country or region.

6.8.1. Scenario B

Scenario B is characterized by the application of a Smart Roads Classification (SRC) system with no existence of a digital infrastructure. Under these assumptions, Road Administrations (RAs) and Operators (ROs) are responsible for the application of the SRC in terms of identifying and signaling the road segments that present better characteristics to be driven by SAE level 2-3 vehicles in an automated way. In this context, only the lowest Smart Road Levels –Humanway (HU) and Assistedway (AS)– are expected to be defined.

RAs and ROs will determine the Smart Road Level (SRL) of a road segment based on the thresholds defined in the SRC. As data about disengagements and ODDs are not available, the SRL will depend on the physical characteristics of the infrastructure –road typology, the geometric design of the road, pavement characteristics, road signage, and all other physical factors related to the road and its environment–. Figure 65 shows a basic example of the determination of SRLs. All factors should be considered, but for simplicity reasons, only the horizontal alignment is shown. Assuming that curve radii lower than 350 m are prone to cause disengagements in SAE level 2-3 vehicles –driving at the posted speed limit on that two-lane rural road (80 km/h)– the road segment consists of three Operational Road Sections (ORSs).

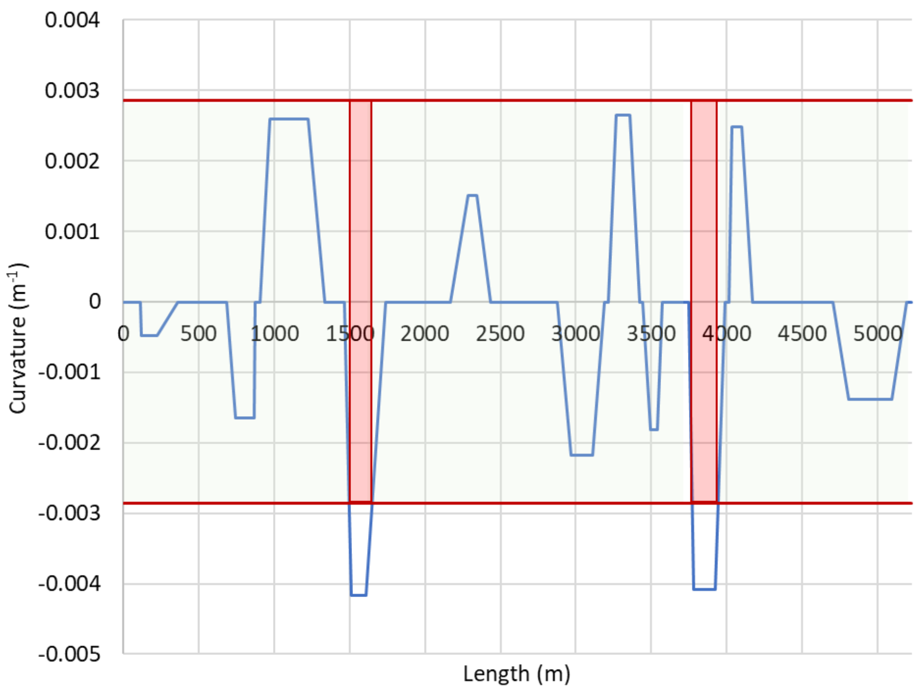

Figure 65. Use Case Scenario B – Applying thresholds.

Each ORS, including those locations causing disengagements (HU), will be signalized by means of advisory or warning signs, as applicable (Figure 66). This will make road users aware of potential disengagements and encourage them to activate/disable the driving automation system. It is expected that road users will increase their confidence in automated systems as the SRC system is implemented. An accurate determination of the thresholds is necessary for this purpose (see below).

Figure 66. Use Case Scenario B – Signaling of road segment.

However, the same procedure must be followed considering other physical factors and, then, the overlapping of the individual identification of compliance with the proposed thresholds will result in the ORSs. Table 39 shows a tentative checklist that could be already used for the identification of ORSs, including conservative thresholds.

Domain	Parameter	Threshold
Horizontal alignment	Minimum Radius (m)	see Table 40
Vertical alignment	Minimum K (m/%)	>= 10
Cross-section	Lane width (m)	[2.8; 4.0]
Road marking	Width (mm)	>= 150
Road marking	Contrast	1:3
Road marking	Retroreflectivity (mcd/m2/lx)	>= 150
Road marking	Continuity	Yes, including on entrance/exit ramps
Speed	Posted Speed Limit (km/h)	see Table 40
Pavement	IRI (m/km)	<= 3.5

Table 39. Checklist to determine AS ORSs in Scenario B.

Posted Speed Limit (km/h)	Minimum Horizonal Curve Radius (m)
70	250
80	350
90	400
100	500
110	600
120	800

Table 40. Relationship between Posted Speed Limit and minimum horizontal curve radius for AS ORSs identification (Rounded values from García et al. [1]).

These thresholds must be as accurate as possible. AS road segments should not present many disengagements, while HU road segments should not be very adequate for automated driving. These thresholds should be determined with massive research campaigns, involving many different vehicles operating on the road network. Additional SRL may be necessary if differences across models are too high. The thresholds indicated above have been obtained from existing literature.

Additionally, a minimum length for ORSs should be established –e.g., 1 km, but further research is needed– to ensure safe and comfortable Operational Road Sections (ORSs). This means that two nearby road sections that are prone to cause disengagement would lead to a longer HU road section (Figure 67). Additionally, the density of disengagement per kilometer might also be used to establish final ORSs but further research is also needed in this regard.

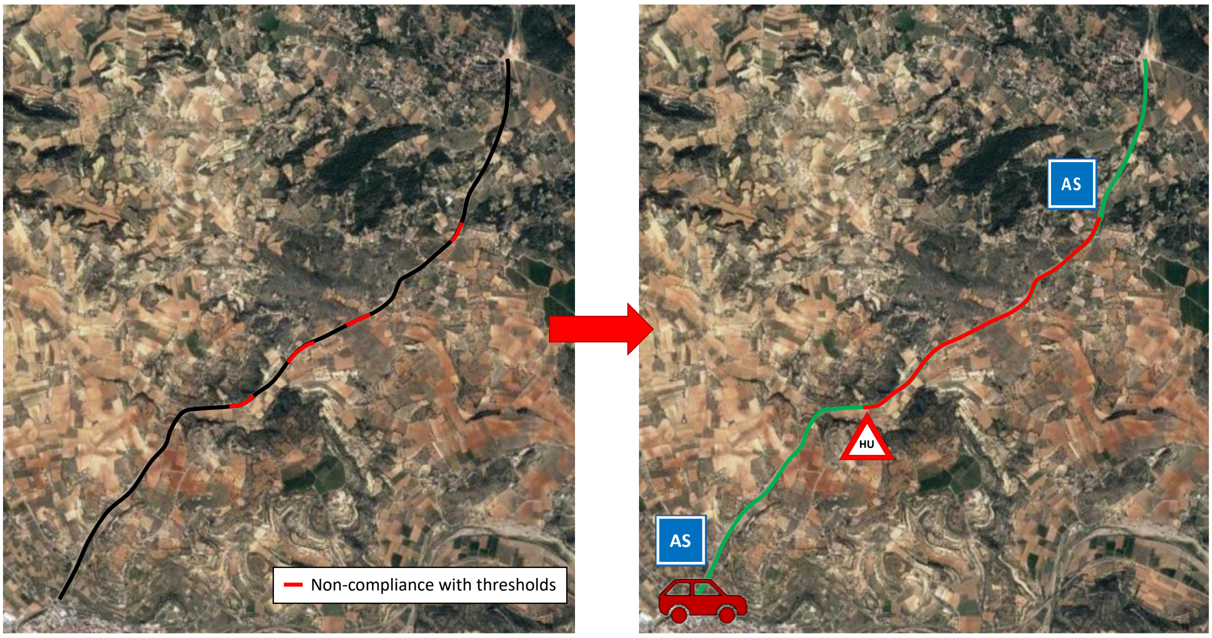

Figure 67. Use Case Scenario B – Signaling of road segment with nearby HU road sections.

Last but not least, it should be noted that the application of the SRC at initial stages should be focused on main corridors and the primary road network –motorways, freeways, and most important multilane highways–. Two-lane rural roads should be considered at more advanced stages when some experience has been gained.

6.8.2. Scenario D

This scenario is similar to scenario B –application of an SRC considering SAE level 2-3 vehicles– adding a digital infrastructure and the availability of information about disengagements. While digital infrastructure will allow Road Administrations (RAs) and Operators (ROs) to provide valuable information for vehicles about road geometry, traffic, environment, events, etc., disengagement information will allow them to determine the Smart Road Levels more accurately.

In this context, three levels of SRLs are expected: Humanway (HU), Assisteway (AS), and Automatedway (AT). Specifically, AT road sections are associated with AS road sections that present connectivity support. Additionally, Variable Message Signs (VMS) could be used when unstable connectivity, shifting between AT and AS.

In Scenario D, RAs and ROs will define ORSs based on disengagements, which will be reported by the automotive industry (OEMs) or by CAVs, even sharing this information to connected vehicles in real-time. To do that, an Information Management Centre or Provider (IMP) will be necessary, which should be led by RAs and ROs, as appropriate. This would allow changing the SRL of a road section depending on the circumstances or conditions at any time. As a result, RAs and ROs would be able to identify robust Operational Road Sections (ORSs), defined as the ORSs that do not experience SRL changes due to dynamic factors. Similarly, the ORS that are extremely likely to change their level could be defined as shifting ORSs.

Figure 68 shows the application of the SRC on robust ORSs. RAs and ROs identify HU road sections from the disengagements reported by OEMs or CAVs –thresholds should be studied for the maximum disengagement density and frequency rate–. This is an important difference with Scenario B, which relied on previous studies to define the thresholds. This scenario allows a much more accurate definition of thresholds, as well as dynamic changes based on this information.

In this case, an AS operational road section (in yellow in Figure 68) is identified. According to the AS definition, this section allows SAE level 2-3 vehicles to perform in an automated way with low number of disengagements and with no V2X support. The green portion represents a road segment that additionally presents V2X support (i.e., an AT Operational Road Section). As these ORSs are robust, the SRLs should be indicated with fixed signs. The AT segment will also present digital information with its characteristics.

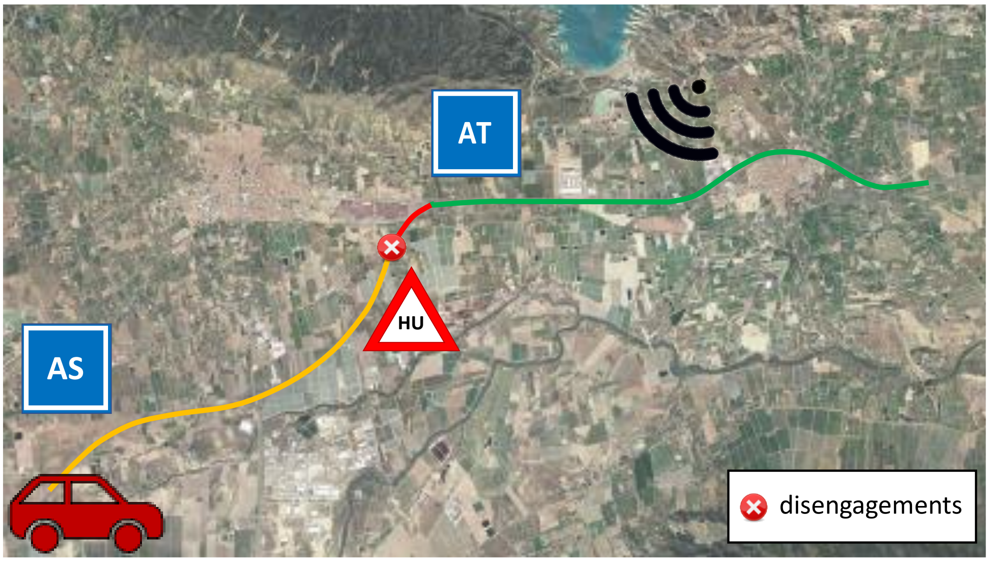

Figure 68. Use Case Scenario D – Signaling of robust operational road segments.

By contrast, a similar road segment presenting some connectivity issues under certain situations –e.g., under unfavorable weather conditions– should consist of Variable Message Signs at these locations where the Smart Road Level usually changes (Figure 69). In this way, road users will have more accurate information about the performance of their vehicles, increasing user acceptance and safety.

The reported disengagements and the issues that downgrade the SRL could be analyzed by the automotive industry to enhance Connected and Automated Vehicles (CAVs) performance and by Road Administrations and Operators, to maximize the length of the Operational Road Sections. Likewise, RAs and ROs will obtain great benefits of this scenario as they will be able to identify and prioritize road investments, i.e., in which road segments is more profitable to invest in terms of digital infrastructure.

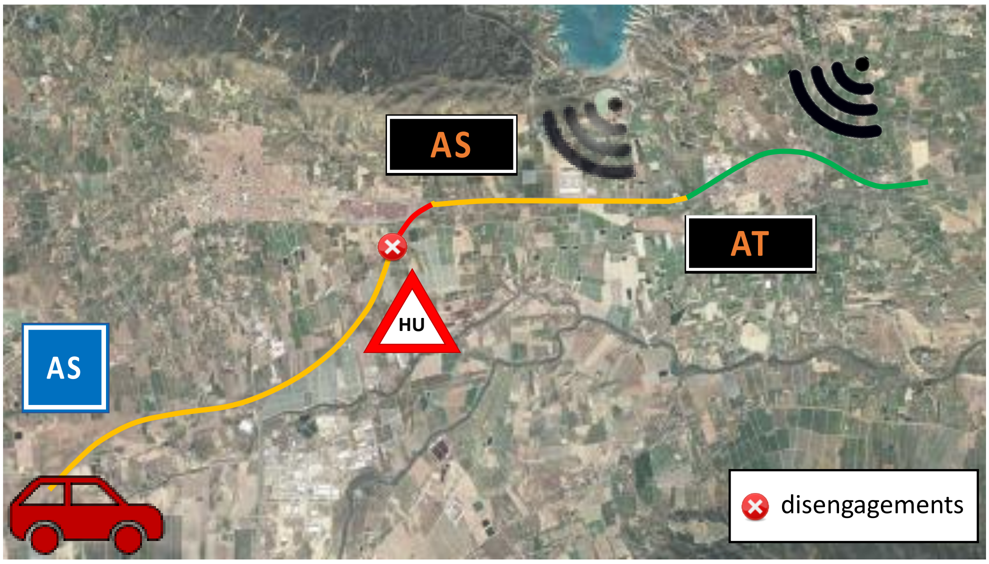

Figure 69. Use Case Scenario D – Signaling of shifting operational road segment.

In case no information on disengagements is available –Scenario C–, the identification of those Operational Road Sections not allowing an automated driving –HU sections– could perform considering similar thresholds to those proposed in Table 39 and Table 40. To this regard, updated thresholds are expected since Scenario D will appear in a medium-term.

6.8.3. Scenario G

The conditions of Scenario G are similar to Scenario D –consisting in the application of a Smart Roads Classification with the availability of digital infrastructure and disengagement information– but with the existence of SAE level 4 vehicles. Unlike the previous Scenario D, a more sophisticated digital infrastructure is managed by ROs, IMPs, and MNOs. To achieve high Smart Road Levels –e.g., Full Automatedway (FA)– the digital infrastructure should provide information such as traffic data, events, Variable Message Signs, or performance microdata. This information could be retrieved by third parties, but the combination to reflect all inputs would probably require a unique stakeholder like the RO or an IMP. These data will be used by OEMs to provide vehicles with infrastructure data through HD maps. SAE level 4 vehicles will be able to compare this information to their limitations and determine dynamically when they are entering into an ODD-compatible section, and when they are exiting from them. Safe harbors could also present dynamic data –such as occupation– that would enrich the information for drivers.

In this context in which low-end SAE level vehicles coexist with SAE level 4 vehicles, information management becomes crucial. RAs and ROs will still have to indicate by means of physical signage the Smart Road Levels, whereas SAE level 4 vehicles will be able to receive this –and additional– information from the digital infrastructure or even from other vehicles using ad-hoc networks.

Like in Scenario D, RAs and ROs will define ORSs based on disengagements, which will be reported by CAVs. This information will also be shared with connected vehicles in real-time. In this way, RAs and ROs could modify the Smart Road Level of an ORS or communicate possible disengagement ahead in real-time in case of non-frequent and unusual disengagements are reported at a certain location.

In this stage, the highest SRL –Autonomousway (AU)– might be achieved on those Operational Road Sections with restricted or controlled access. For instance, some ORSs on freeways might include Dedicated Lanes only for SAE level 4 vehicles.

Like in Scenario B, RAs and ROs will determine the SRLs based on the thresholds defined for each factor in the Smart Roads Classification. However, these thresholds are expected to be more accurate in this scenario as the research and technology will have progressed. In turn, SAE level 4 vehicles might achieve a cooperative driving as long as the infrastructure will be ready for that.

In case no information on disengagements is available –Scenario F–, the determination of the Smart Road Level of the Operational Road Sections (ORSs), including the identification of those ORSs not allowing an automated driving –HU sections– could perform considering similar thresholds to those proposed in Table 39 and Table 40, also adding factors related to connectivity and digital infrastructure. Regarding this, it is expected that the thresholds for each SRL will be updated in line with technological progress.

6.8.4. Scenario H

This scenario represents a long-term situation in which CAVs have been well adopted. SAE level 4 vehicles with comprehensive ODDs exist and are generalized. Some SAE level 5 vehicles may exist but will barely differ with SAE level 4 vehicles on rural environments (the main difference would probably rely on urban ones).

The digital infrastructure is also well established, and connectivity and coverage extend to almost the entire road network. Combined with the ODD capabilities of vehicles, most road segments could be classified as Full Automatedway (FA).

This situation leads to a simplification of who, when, and how manages the road. Information would be in real-time, and IMPs would probably exist to cooperate with Road Operators to manage the traffic by using advanced algorithms and massive data. As a result, most road management would be automatic.

Like in Scenario G, a sudden increase of Take Over Requests at some zones may result in an immediate reduction of the Smart Road Level or automated warnings to nearby vehicles. Immediate reroute planning could be sent to more distant vehicles.

Road Administrations should decide which road facilities may be AU or stay in FA conditions. In the planning stage, RAs should decide whether support for cooperative driving is provided to these road segments. This support should be provided if the infrastructure is considered to be critical.

Probably, many freeway sections would keep at least one lane as FA, but would automatically determine the number of AU road lanes (Dedicated Lanes) depending on the SAE level 4+ vehicle density and the general traffic volume. This would be something that could take place in the management stage.

6.9. SRC ADAPTATION TO LMICS

The first important particularity associated with LMICs is their road network. Generally speaking, these countries present a much less dense road network that may present bad conditions and low adaptation to standards.

Questionnaire 1 included some global factors to capture this situation at a national level. These factors were related to economy, road network state (investment and condition), and connectivity level (see Appendix A4.1 Questionnaire 1), and were used to classify the participating countries upon their particularities. These data were obtained from worldwide well-known organizations like the World

Health Organization (WHO), the World Bank, or the Organization for Economic Co-operation and Development (OECD).

Table 41 shows four rankings of the participating countries in Questionnaire 1 based on (i) Economy, (ii) Road network, (iii) Connectivity, and (iv) Global classification considering all these factors. These rankings were obtained by using k-means clustering, considering the values of the variables retrieved for each factor (see Appendix A4.1 Questionnaire 1). All analyses were developed by grouping the countries into four clusters, being 0 the highest level and 3 the lowest level.

Considering those countries obtaining a level 2 or 3 related to the Global ranking, some remarks can be done and extrapolated to LMICs. These countries reported that only high-capacity highways – freeways and motorways– had the features requested for applying the SRC. Particularly, they indicated that multilane highways and two-lane rural roads do not have enough road marking width (< 150 mm), pavement condition is qualified as “fair” or “poor”, and the road marking configuration would “sometimes” or “rarely” allow automated driving. Additionally, these countries reported poor communication facilities as both the DSRC/ITS-G5 availability and 5G availability were informed to be very low (1 on a Likert scale from 1 to 5).

Country	Economy	Road network	Connectivity	Global
United States	0	0	0	0
Austria	1	1	0	1
Denmark	1	1	0	1
Finland	1	1	0	1
Portugal	1	1	0	1
Singapore	1	1	0	1
Spain	1	1	0	1
Sweden	1	1	0	1
Switzerland	1	1	0	1
Andorra	1	2	0	1
Australia	1	2	0	1
Belgium	1	2	0	1
Canada	1	2	0	1
France	1	1	1	1
New Caledonia	1	2	0	1
Norway	1	2	0	1
Korea	2	1	0	1
United Kingdom	1	2	0	1
Czech Rep.	2	2	0	1
Italy	1	2	1	1
New Zealand	1	2	1	1

Country	Economy	Road network	Connectivity	Global
Slovakia	2	2	0	1
Slovenia	2	2	0	1
Chile	2	2	1	1
Mexico	2	2	1	2
Albania	3	2	1	2
Algeria	2	2	2	2
Bolivia	2	3	1	2
Colombia	2	3	1	2
Iran	2	3	1	2
Peru	2	3	1	2
Russia	2	3	1	2
South Africa	2	3	1	2
Tunisia	2	3	1	2
Burkina Faso	3	3	1	3
Nigeria	3	3	2	2
Mozambique	3	3	3	3

Table 41. Ranking of countries participating in Questionnaire 1.

Therefore, the global priority of these countries should be set to shift from Humanways (HU) to Assistedways (AS) as many roads as possible (see Scenario B, including its description, business models, and use case). In addition, if the situation of the country allows it to plan and construct new road facilities, these should be designed to achieve the highest LOSAD.

These countries would probably present difficulties at deploying a sound set of RSUs for V2X communications. Instead, their actions should be directed towards expanding their 5G coverage, at least along their main corridors, given that high Smart Road Levels (SRLs) could be achieved from ad-hoc V2V networks.

Access to information by RAs is also a limitation here. Actually, information is key to prioritize actions and determining the current LOSAD/ISAD levels of the infrastructure. Probably, LMICs would present shortcomings at classifying their road network due to the lack of a road infrastructure information system. Instead, they might need to determine which road facilities would have the highest impact – in terms of traffic volume and safety issues–, and expressly determine their LOSAD/ISAD levels that will define the Smart Road Level.

Moreover, the lack of a comprehensive classification of their road networks would prevent these countries to prioritize the actions to take in the same way as expressed in the general workflow. The AADT has been suggested as an adequate surrogate indicator to maximize the impact of the outcome, but there are other possible indicators, such as a higher crash rate.

The proposed Smart Roads Classification system, specifically through the defined scenarios (see 6.6. 6.6. Scenarios), will guide the future of LMICs for no-regret investments and some of the low-cost measures could be applied, starting with upgrading Humanway (HU) to Assistedway (AS) some of the main highways or corridors –motorways, freeways, and most important multilane highways–.

Considering the inadequate state and low adaptation to standard condition of many features of the road infrastructure, the upgrading of some highways to Assistedway (AS) will encourage safer roads for both human-driven vehicles and automated vehicles. Therefore, the benefits will be higher than in other countries with this first step. For that purpose, pavements must be free of damage (potholes) and major irregularities, road markings must be wide enough, continuous, and in good enough condition to be visible, vertical signs must be adequate, and so on.

Therefore, the criteria included in the SRC proposal for achieving an AS Smart Road Level will mean no-regret investments just for the mentioned compatibility with the current vehicle fleet, although the introduction of new automated vehicles will be slow but progressive.

The benefits of the Special Project, mainly for LMICs, will not only focus on connected and automated driving, but also on their economic development. Regarding this, the definition of road investment plans by applying the proposed Smart Roads Classification will allow LMICs to get a reliable, resilient, and more efficient road network that will help economies grow by connecting markets and easing the flow of goods, people, and services.

7. CONCLUSIONS

7.1. DESCRIPTION OF SRC

The increasing penetration of Connected and Automated Vehicles (CAVs) on the road network requires the development of a road classification system that provides information to users and vehicles on their degree of adaptation to smart driving. In this context, **this Special Project arose with the aim of exploring the feasibility of a new framework for the classification of the road infrastructure based on its physical characteristics as well as on its reception capacity of the automation and connectivity with vehicles**.

A Smart Roads Classification (SRC) has been proposed based on two indicators: Level Of Service of Automated Driving (**LOSAD**), that is related to automated performance, and the Infrastructure Support Levels for Automated Driving (**ISAD**), which is associated with connectivity support.

The LOSAD is categorized in five levels, from A to E, being determined as a function of how ready the road infrastructure is to support automated driving (Table 42). The most important parameter is the distribution of their Operational Road Sections (ORS). ORSs can be defined as every section that fully supports automation for all driving automation systems with explicit Operational Design Domains (ODDs), i.e., a section that should be ideally driven by any driving automation system. On the other hand, **the ISAD levels** are those defined by the INFRAMIX Project [4], **from Level A supporting cooperative driving to Level E associated with conventional infrastructure with no digital infrastructure** (Table 43).

LOSAD Level	Description
A	The road segment is compatible with the vast majority of vehicle ODDs. SAE level 4 vehicles will not request human intervention. SAE level 3 vehicles may experience very rare disengagements. SAE level 2 vehicles may experience very low number of them.
B	The road segment presents similar physical characteristics than LOSAD A. Dynamic aspects such as weather may limit some vehicles, requesting human intervention or presenting very few disengagements.
C	The road segment is not fully compatible with all known ODDs. Drivers are encouraged to activate their driving automation systems but being aware if any takeover request or disengagement appears.
D	The road segment presents fair compatibility with some ODDs. Drivers of SAE level 3-4 vehicles may activate their systems, being aware of the road and traffic conditions. Drivers of SAE level 2 vehicles are discouraged from doing so.
E	The road segment presents nearly null compatibility with most automation systems. Drivers should perform in manual mode.

Table 42. LOSAD levels.

ISAD Level	Description
A	The road segment supports cooperative driving: the infrastructure can perceive information and give orders to vehicles to improve safety and traffic operation.
B	The road segment supports cooperative perception: vehicles can inform the infrastructure through V2I about microscopic traffic and road conditions.
C	Digital information about the road segment is available (such as HD maps). Dynamic information (e.g., signs, weather, etc.) is regularly updated.
D	Static digital information available. This information is not updated in real time.
E	Conventional infrastructure with no digital support.

Table 43. ISAD levels.

Although Road Administrations and Operators could directly use LOSAD and ISAD to identify the Smart Road Level (SRL) of a road segment, this may not be ideal for management purposes. Thus, diverse underlying factors related to LOSAD and ISAD have been defined and grouped into the following categories: (i) physical infrastructure, (ii) digital infrastructure, (iii) connectivity, and (iv) road users. In this way, checklists with these factors have been proposed to be used by Road Administrators and Operators to determine the SRL of a road segment.

A total of five Smart Road Levels (SRLs) have been defined as a result of the feasible interactions between the different LOSAD and ISAD levels, depending on how ready the road is to host CAVs (Table 44).

Smart Road Level	Description
Humanway (HU)	The road segment is not ready to host CAVs, due to the high number of disengagements, and/or the low capability to share digital data to inform vehicles about their ODDs.
Assistedway (AS)	The road segment is adequate to perform autonomously, but this condition may stop due to different factors (not as frequently as HU segments). Therefore, drivers of automation SAE levels 1 to 4 vehicles should be attentive to the road to disengagements or takeover requests.
Automatedway (AT)	The road segment presents reasonably good connectivity and physical infrastructure capabilities, so disengagements or takeover requests would be quite lower compared to AS and HU. Vehicles can match their ODD limitations with the digital information shared by the road segments, so most takeover requests (SAE levels 3-4) are planned.
Full Automatedway (FA)	The road presents a continuous ORS, ensuring ODD compatibility with far most SAE level 3-4 vehicles. Digital information is shared, so these vehicles can plan any takeover request. Therefore, an experience without disengagements can be attained. SAE level 2 vehicles would experience very low number of disengagements.

Smart Road Level	Description
Autonomousway (AU)	Similar than FA, the connectivity infrastructure supports cooperative driving, so the infrastructure can receive and transmit tailored instructions to all vehicles, micromanaging traffic performance. This road segment type is exclusive for SAE level 4-5 CAVs. This highest smart level may be designated to some lanes.

Table 44. Smart Roads Levels.

The proposed Smart Roads Classification (SRC) system includes the ideas and thoughts of all stakeholders –Road Administrations and Operators, Automotive industry, Road consulting firms, Academia, and Research institutions–. A preliminary version of the system was consulted internationally by means of a questionnaire in which 65 people from 33 countries around the world participated. A webinar attended by 162 people from 67 different nationalities was also organized to retrieve feedback and share the model.

7.2. Feasibility analysis of SRC Application

After defining an SRC system, a feasibility analysis of its application was developed by identifying its benefits and opportunities, exploring its challenges and barriers, analyzing its interaction with existing road classification systems, and defining a set of plausible, future scenarios with the analysis of their possible business models.

An SRC will contribute to an efficient planning of investments on physical and digital infrastructure and promote a safer, more efficient, sustainable, and comfortable road network. Compared to other existing road classification systems, an SRC can be real-time updatable and assist Road Administrations and Operators to inform users and vehicles about the road performance. Moreover, an SRC could help create a common international framework for all stakeholders. It could be used as a guiding inception, providing a basis for work and dialogue among stakeholders, especially between Road Administrations, Road Operators, and the automotive industry.

Regarding challenges and barriers, the lack of coordination and cooperation between stakeholders is the most important issue. The findings of the project support the **high reluctance of the automotive industry to explicit the limitations of its driving automation systems** as no response were obtained for Questionnaire 2 –designed for this stakeholder– and only one response in Questionnaire 3. From the infrastructure side, a harmonization of the discrepancies among different road authorities within the same or adjacent regions must be addressed. This harmonization does not necessarily imply convergence towards a common standard, but rather identifying which of the current standards are critical and should be reviewed. Likewise, an SRC should be consistent with existing road classification systems. Undoubtedly, **a legislative framework that includes the assignment of responsibilities is of utmost importance**. Finally, the cost of the SRC implementation is one of the main obstacles.

The huge uncertainty about the future evolution does not allow forecasting a clear situation in a short-, medium-, or long-term. For this reason, a total of eight scenarios have been defined for different moments, considering some possible situations related to the existence and/or application of a Smart Roads Classification, the SAE levels of vehicles, presence of digital infrastructure, and data availability (Table 45).

Scenario	Description
A	This scenario is a near-to-come one, in which an SRC does not exist or is not applied, serving as a reference scenario. Most vehicles do not present automation capabilities (like nowadays), but SAE level 2 vehicles are becoming more and more common. The first SAE level 3 driving automation systems are slowly showing up.
B	This situation is an alternative version to Scenario A, in which a Smart Roads Classification system has been implemented. Given the existence of SAE levels from 0 to 3, Humanway (HU) and Assistedway (AS) road segments could be identified.
C	This scenario is similar to scenario B, adding a digital infrastructure. Since this scenario is focused on the short-term, the digital infrastructure will not probably support cooperative perception or driving. In addition to the HU and AS smart levels, Automatedway (AT) level can appear in Scenario C along road segments presenting connectivity support and good conditions to be driven autonomously.
D	This scenario is similar to scenario C, but information about disengagements is available so the Smart Road Level of the different Operational Road Segments can be determined in a more accurate way.
E	This medium-term scenario could be considered as a natural evolution of scenario A, without the application of an SRC, also serving as a reference scenario. SAE level 4 vehicles are hitting the market, with capability to perform without the driver intervention along road segments that meet their Operational Design Domain.
F	This scenario is similar to Scenario E but having a Smart Roads Classification. A Digital Infrastructure also exists, but probably more sophisticated compared to Scenario C, given the data requirements of some Smart Road Levels.
G	This scenario is similar to Scenario F but having public information about disengagements. Again, this is a major advantage for road management.
H	In a long-term scenario, most vehicles will present some kind of automation, including SAE level 5 ones. A robust digital infrastructure will exist and will be available at most locations. On the contrary to other above scenarios, an SRC is completely necessary to clearly identify the locations where only SAE level 4+ CAVs are allowed.

Table 45. Description of plausible scenarios.

The most important relationships between the stakeholders in each scenario have been outlined, highlighting the specific needs and opportunities that may affect the entire ecosystem. It is worth noting that those scenarios requiring the deployment of Digital Infrastructure (C to H) involve substantial investments and maintenance costs. Related to this, diverse ways of accommodating investments, payments, or cost during the provision of the service –including possible options to obtain revenues– are proposed considering each stakeholder and alternative. Additionally, a brief techno-economic study is shown to provide a more solid insight about the investment cost.

Finally, some use cases concerning different scenarios (B, D, G, and H) have been developed to facilitate all stakeholders the application of an SRC under diverse situations that could be given in any country or region. Particularly, some recommendations are presented for the application of an SRC in Low- and Middle-Income Countries (LMCIs). These countries should start with upgrading Humanway (HU) to Assistedway (AS) some of the main highways or corridors. Considering the inadequate state and low adaptation to standard condition of many features of the road infrastructure, this upgrading will lead to safer roads for all road users –human-driven vehicles and automated vehicles–. In addition, if the situation of the country allows planning and constructing new road facilities, these should be designed to achieve the highest LOSAD.

7.3. Recommendations

As this Special Project presents an exploratory study on the establishment and application feasibility of a Smart Roads Classification, this section aims at proposing steps that could be followed for a successful initial deployment of the system. Diverse follow-up proposals are described considering all stakeholders. These actions or commitments arose from responses reported by participants in Questionnaires 1 and 3, POT's thoughts and reflections, and feedback retrieved throughout the webinars.

Pilot tests remain as a key factor, where the cutting-edge capabilities of connectivity and automation can be checked on existing road facilities and under real-world traffic conditions. The final business models involving all stakeholders should be determined and agreed upon after analyzing the results of different use cases as trials in the application of SRCs. The role of every stakeholder at the planning, investment, and management stage should be adopted based on technical, economic, and financial evaluations.

7.3.1. Road Administrations (RA) and Operators (RO)

The application of a Smart Road Classification could not be immediate and should be restricted to pilot tests focused on some main highways, and controlled road network first.

The **first level of application** would be on the road segments that are about to trigger too many disengagements, i.e., the automated driving system transfers control to the driver with some frequency. In these cases, drivers should disable driving assistance. According to the proposed SRC model, these correspond to the Humanway (HU) road segments. This identification should be physical –with signs– so drivers of SAE level 2-3 vehicles should keep manual control, as if the vehicle was not automated. At this initial stage, this is the expected behavior but there is no direct evidence about disengagements.

The **second level of application** would be on the road segments that are about to present good conditions to be driven autonomously. Drivers would be encouraged to enable their driving automation system while keeping attention on the road. According to the proposed SRC model, these correspond to the Assistedway (AS) road segments. This identification should also be with signs, indicating that drivers of SAE level 2-3 vehicles may activate their driving automation systems. However, they should always keep attention on the road.

RAs and ROs could establish as a priority the designation of these road segments as freeway/highway, which would correspond to a smooth geometric design, continuous road markings in good state, adequate signage, and undamaged pavements.

It is important to highlight that the **physical signs to identify these road segments are just advisory**, informing the drivers about the smart capabilities of the road segment but not forcing them to enable/disable the driving automation system. Where Variable Message Signs exist, the new smart road level signs could be included, allowing for some dynamic management of smart levels when there are factors that are more restrictive or limiting.

In addition to the HU and AS Smart Road Levels, a new one could be added with special features. Road segments that are likely to present good conditions to be driven autonomously and also present connectivity support should be tagged as Automatedway (AT). Again, a physical sign should indicate this condition to all users, but Digital Information should be also transmitted to Connected and Automated vehicles. Variable Message Signs could be used for road segments with no stable connectivity, shifting between AS and AT.

An alternative Smart Road Level may be defined to the road segments that do not present a Digital Infrastructure but have Intelligent Transport System (ITS) features. These road segments already exist and could be identified as AS* (as long as these are not likely to trigger many disengagements, like AS road segments). Moreover, these would probably constitute a primary target for RAs and ROs to deploy the Digital Infrastructure and convert them into real AT road segments.

The connectivity support allows the Digital Infrastructure to provide valuable information for vehicles about road geometry, traffic, environment, events, etc. SAE level 3 vehicles would result really benefited, since the characteristics of the infrastructure could be transmitted, foreseeing disengagements beyond the line of sight and providing more time between TORs and effective disengagements. Some connected SAE level 2 vehicles could also use this additional information to prevent some disengagements.

Road Administrations and Operators should define which thresholds should be considered to differentiate the smart road levels. Ideally, these should be defined based on the disengagements or ODD information provided by vehicle manufacturers and/or suppliers. Since this information is not available at the beginning, it is recommended these thresholds to be established upon research that determines which factors and thresholds are more likely to trigger vehicle disengagements. Given the variety across driving automation system technologies, conservative thresholds should be established for posting these advisory signs using current findings from research.

At the same time, information campaigns should be launched to make drivers aware of the capabilities of their SAE level 2-3 vehicles and on which road segments they will be able to use them safely. These pilot tests under controlled conditions should be used before the SRC is extended to the rest of the road network.

In general, best practices and the findings derived from the first applications of an SRC should be shared to start the necessary capacity building, skill development, and change in the administrative organization of Road Administrations. Moreover, it will be necessary the development of a standardized legal framework concerning road traffic safety, including the smart roads and the minimum specifications for CAVs.

It is important to highlight that the SRC framework will in the medium-term become more visible and better understood through the different services provided cooperatively, which imply greater safety. In any case, a change in road and traffic regulations will be necessary –e.g., to include the necessary new signs–.

Finally, it will be necessary a high-level technical assistance. Many expert consultants will be needed to advise RAs and ROs about how to determine and apply the most appropriate SRC for their constraints and interests. The development of guidelines for the application of an SRC should provide the necessary support.

7.3.2. Automotive Industry (OEM and TIER1)

One of the key issues to be addressed is related to **how the automotive industry may be engaged in the development and application of the SRC**. Some proposals for Road Administrations (RA) and Operators (RO), seeking collaboration with the automotive industry, are as follows:

- Not to interact with single OEMs, but to **collaborate with OEM platforms** so as to know and understand the challenges and goals of the automotive industry.
- **Discuss on SRC development and application within automotive meetings, forums, and standards**. RAs and ROs should participate in the UNECE World Forum for Harmonization of Vehicle Regulations (WP.29) discussion on technical requirements for automated vehicles.
- **OEMs are encouraged to provide information on disengagements**. This information could be used to better define the Smart Road Levels –especially the lowest ones–. For the first pilot tests it would be very useful if some of them could participate by providing such information. If this is not possible, it could be obtained indirectly by observing the automated driving system performance of a large sample of CAVs.
- Automotive industry should provide detailed information on the infrastructure **requirements for the diverse LOSAD and ISAD levels**, with special attention to different scenarios and environments.
- Automotive industry should clearly **identify and certify factors and thresholds characterizing ODDs for theirs CAVs**. In this regard, manufacturers should be honest about their vehicles' capacities and limitations. In return, confidentiality should be guaranteed by SRC developers.
- Automotive industry may be engaged in the development of the SRC by **establishing a tight connection with road infrastructure (RAs and ROs) and connectivity providers (MNOs)**. It should be a process of exploring global weaknesses which should be strengthened even from the side of the automotive industry or could be supported by the road authorities. It should be effective to conduct research in collaboration with automotive manufacturers.

7.3.3. Mobile Network Operators (MNO)

This stakeholder consists of providers of the wireless connectivity that could serve as a basis for C-V2X communications. They should be involved in the application of a Smart Road Classification through pilot tests focused on some main highways, being able to designate some smart road segments as Automatedway (AT) by providing a good connectivity level.

7.3.4. Users

Road users are at the center of the SRC proposal. **To encourage a safe and efficient driving, users must be informed about the capabilities of their automated vehicles and their compatibility with the itinerary they are willing to cover**. To this regard, some suggestions on how best to convey the SRC framework to road users are:

- RAs, ROs, and Information Management Providers (IMPs) should inform road users –drivers and CAVs– about the Smart Road Level (SRL) of each road segment, through physical road signs, variable roadside signaling and in-vehicle application notification. Depending on the level of connectivity of the vehicle, there could be a direct communication of the SRLs with the vehicle. In-vehicle notifications will be displayed to the user through the Human Machine Interface (HMI).

- The vehicle itself, without connectivity, will be able to know the static SRL of the road, just as navigation systems currently know the speed limit of the road. Digital maps are useful for making users aware of how ready a road network is for an automated driving. In any case, a "fail-safe backup" could be a specific signage on the road.
- A clear indication through digital information, customized to the specific automation system level of the vehicle would be preferable.
- The SRC must be very simple, establishing SRLs for sufficiently long sections within the road network, i.e., without frequent level changes.
- GPS navigation systems may include this information as criteria for routing. For operation, SRC and ODD-compliant zones should be part of the data used by the navigation tools.
- Standardized messages should be established. The framework communication should come from a trustworthy stakeholder, such as a road authority. In any case, the message should be authorized by a road authority.
- Full transparency should be applied within the SRC framework for road users.
- Different road users –customer segments– could be identified and their needs analyzed. In this way, tailored messages could be provided to meet the specific needs of each type of user.

However, **to launch an SRC it is absolutely necessary that road users know and learn about CAVs, smart roads, their classification, and how to use their vehicles on them so as to ensure a safer, more efficient, and sustainable driving**. Different measures could be used for that purpose, including education, initial training and especially for existing drivers, such as:

- A new supplement for educational programs.
- Driver's license test should include new regulations and issues related to the SRC.
- Through the manual and training materials, as a package, of their own vehicle when buying it. A mandatory acknowledgment of understanding of the SRC framework should be checked when activating an automated driving function on the vehicle.
- Specific road safety campaigns to raise public awareness and specific training for current road users. For this purpose, different means can be used, such as:
    - Social networks or apps designed for this aim.
    - Pilot programs for general dissemination.
    - Easily assimilated information capsules that can go viral.
    - Mobile and wearables devices.
    - Advertisements and use tests on TV, internet, or leaflets in service areas.
    - Insurance leaflets.
    - Via public and private institutions, not only RAs.

7.3.5. Information Management Providers (IMP)

Once the Digital Infrastructure shows up in the road environment and connected vehicles become a reality, a lot of information related to performance, pavement condition, road maintenance, etc. will be shared. There is a necessity to **collect, process, and share** this **information with the adequate stakeholders**. Information Management Providers covers the stakeholders that will intervene in this process. Other stakeholders such as services providers, trip planners, MaaS providers are part of this group.

To facilitate the creation and development of these companies and providers, including start-ups, RAs and ROs should share all available data on physical and digital infrastructure and their state. In logical reciprocity, they should share the results of their analysis with RAs/ROs, not only with their customers.

7.3.6. PIARC

It is not recommended that PIARC undertakes another Special Project on the same topic or creates a specific Technical Committee until smart roads become substantially more mature. However, other **actions promoted by PIARC** could be undertaken, such as:

- Include SRC in the Terms of Reference (ToR) of a new Task Force on CAVs.
- Involve PIARC as an observer in some research projects that discuss on CAVs and their interaction with the road infrastructure and operation.
- Take a more active role in working directly with established and well-known international organizations, such as CCAM partnership of the European Commission, SAE, ERTICO, TRB, or ITE.
- Develop or promote a series of webinars/conferences worldwide for the deployment of smart roads and their classification, always ensuring the participation of all stakeholders.
- Motivate some member countries to establish public-private partnerships to develop some use cases of SRC application as pilots, involving OEMs and exchanging data.

7.3.7. LMICs

In general, these countries **present a much less dense road network, with less highways, in poor conditions, and low adaptation to standards**. Therefore, the **global priority** of these countries should be set **to shift from Humanways (HU) to Assistedways (AS)** as many roads as possible. In addition, if the situation of the country allows it to plan and construct new road facilities, these should be designed to achieve the highest Smart Road Levels (SRLs).

These countries would probably present difficulties at deploying a sound set of digital infrastructures and V2X communication facilities. Instead, **their actions should be directed towards implementing and expanding their 5G coverage**, at least along their main corridors, given that high SRLs could be achieved from ad-hoc V2X networks.

Access to information by RAs is also a limitation here. Actually, information is key to prioritize actions and determining the current SRLs of the infrastructure. Probably, LMICs would present shortcomings at classifying their road network due to the lack of a road infrastructure information system. Instead, they might need to determine which road facilities would have the highest impact –in terms of traffic volume (AADT) and safety issues (higher crash rates)–, and expressly determine their factors –LOSAD/ISAD levels– that will define the Smart Road Levels.

The proposed Smart Roads Classification system will guide the future of LMICs for no-regret investments and some of the low-cost measures could be applied, **starting with upgrading Humanway (HU) to Assistedway (AS) for some of the main highways or corridors** –motorways, freeways, and most important multilane highways–.

Considering the inadequate state and low adaptation to standard condition of many features of the road infrastructure, the upgrading of some highways to Assistedway (AS) will encourage safer roads for both human-driven vehicles and automated vehicles. Therefore, **the benefits will be higher than in other countries with this first step**. For that purpose, some road infrastructure improvements should be developed: pavements must be free of damage (potholes) and major irregularities, road markings must be wide enough, continuous, and in good enough condition to be visible, vertical signs must be adequate, and so on.

Therefore, the criteria included in the SRC proposal for achieving an AS Smart Road Level will mean no-regret investments just for the mentioned necessary compatibility with the current vehicle fleet, although the introduction of new automated vehicles will be slow but progressive.

7.4. FURTHER STUDIES AND RESEARCH

Further research is required to determine the details of the SRC that should be applicable to the infrastructure network. Most of this research is oriented to determine which SRC should be applied to the road network.

The **LOSAD concept** requires to be refined to provide valuable information for users, CAVs, RAs, and ROs. Its thresholds should be based on disengagements, combining how many vehicles are affected, and the distance between them. Probably, attentional studies would be an adequate source of information, as well as the information from disengagements provided by OEMs, if it is finally available.

The **factors proposed for ISAD and LOSAD** –and consequently to the SRC– are likely to change once more information about disengagements is known. This includes any change on the thresholds, too. Disengagements become very relevant to determine CAV limitations. If OEMs are invited to share them, an agreement on how and what information becomes available should be undertaken.

Special attention should be given to **ODDs**. There are some ODD taxonomies under development. It is still unknown whether these taxonomies could be robust enough to support all conditions under which a CAV could operate. The main difficulty appears in the interaction of different factors. If these taxonomies are robust, the automotive industry should define and adjust their ODDs to these taxonomies.

If these taxonomies are not robust enough, other ways of expanding ODDs could come from applying Artificial Intelligence (AI) to vehicle disengagements. This could lead to maps for every single driving automation system indicating their compatible ODD zones.

Especially for the high-end SRL, agreements about what is an ORS and how to determine them are encouraged, with special attention to their minimum length. The update cycle would also be important.

It seems unrealistic to count on disengagements in the short-term. Thus, it will be necessary a research effort at determining the capabilities of CAVs on existing roads. The automated driving system performance of a large sample of CAVs could be observed. This is directly connected to determining the automated speed of vehicles along different road features (e.g., horizontal curves, crest vertical curves, visibility restrictions, etc.). Disengagements triggered by road markings should be also studied, by analyzing width, contrast ratio with the pavement, pavement glaring, etc.

Again, in the short-term, many vehicles are expected to rely on physical information from signs. This is why some research effort has to be done in order to extend how Traffic Sign Recognition (TSR) systems interpret some signs –e.g., speed limit signs that do not apply to the current lane–. A debate on which information should be provided at Variable Message Signs (VMS) and how to harmonize it is also suggested.

Finally, some disengagements may come from pavement conditions. The roughness of the pavement may trigger disengagements and should be further studied. Pavement crack seals could also be confused with road markings and, therefore, should be studied too.

The main objectives of **applying an SRC** on the road network are to speed up CAV adoption, enhancing road safety and traffic performance. Therefore, research efforts should be made to clearly demonstrate that an SRC produces benefits in these aspects. Cross-sectional studies could be used to compare the changes in traffic performance with different distribution of SRLs. A safety impact is also expected to be found, especially at the lowest Smart Road Levels.

For the highest SRLs, new road management procedures should be outlined based on data collected and shared with V2X technology.

For the **management of an SRC**, it should be defined how often the current static classification of each road section should be reviewed and what checks should be made. Moreover, all new signs related to every SRL and the corresponding messages for the digital information to be transmitted should be studied, designed, and standardized.

In a long-term, when SAE level 4 vehicles become frequent, some dedicated facilities for Autonomousway (AU) road segments are encouraged. This would require updates on capacity manuals and probably on road design. Special attention should be provided to intersections and interchanges.

In addition, **safe harbors** to enable Minimal Risk Conditions (MRC) should be studied. This includes the definition of the safe harbor standards and the determination of their needs, according to how frequent these should be used. This would probably depend on the traffic volume and the percentage of SAE Level 4+ CAVs on the region.

Throughout the document, a high uncertainty about the **future scenarios** has been presented. There are many research needs to determine which **business models** are expected to be feasible. These technical-economic studies are extremely important, given that they will set the basis for which technology would be recommended in terms of connectivity capacity and cost. Pilot tests remain as a key factor, where the cutting-edge capabilities of connectivity and automation can be checked on existing road facilities and under real-world traffic conditions. The final business models should be determined and agreed upon after analyzing the results of different use cases as trials in the application of SRCs.

The **role of stakeholders** at the planning and investment stage has been outlined. However, different alternative use cases could be adopted based on economic and financial evaluations.

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APPENDICES

A1. SRC Draft Proposal

A1.1 Executive summary

Introduction

This Special Project aims at exploring the feasibility of a new framework for the classification of the road infrastructure. This framework is based on the road physical and digital characteristics and the hosting capacity of connected and automated vehicles.

Given that the presence of Connected and Automated Vehicles (CAVs) is on the increase, it is necessary to explore a new Smart Roads Classification (SRC) system that could provide information to users and vehicles on their degree of adaptation to automated and/or connected driving. An integral road classification system would also allow an efficient planning of public investments on physical infrastructure, by enhancing operativity of driving automation, and on digital infrastructure, by increasing the benefits of connectivity between highways and their users (V2X). End users will be informed about the level of automation they can enable through each road segment. Consequently, a safer, more sustainable and comfortable road network is expected.

This system should be based on existing autonomous driving and connectivity technologies and be highly resilient, so it could be quickly adapted to the technology progress, research findings, and best practices. It should also be compatible with existing road classification systems and the coexistence with other human-driven vehicles and users. Summarizing, the SRC should fulfill the following objectives: common language; useful; universal; standardized; interoperable; robust; consistent; simple; integrable; dynamic; flexible; and no liability for road administrations or road operators.

The Smart Roads Classification Framework

The SRC model is based on two prior parameters: Level of Service for Automated Driving (LOSAD) and Infrastructure Support for Automated Driving (ISAD). The first one represents how ready the infrastructure is to host Automated Vehicles. The second one summarizes the support for connected vehicles.

Level of Service for Automated Driving (LOSAD)

Depending on geometric, environmental, weather and other factors, a road segment may be more or less ready for vehicles to use automation. Five levels are proposed with the following results on automated vehicles:

A	The road segment is compatible with the vast majority of vehicle ODDs. Level 4 vehicles will not request human intervention. Level 3 vehicles may experience very rare disengagements. Level 2 vehicles may experience very low number of them.
B	The road segment presents similar physical characteristics than LOSAD A. Dynamic aspects such as weather may limit some vehicles, requesting human intervention or presenting very few disengagements.
C	The road segment is not fully compatible with all known ODDs. Drivers are encouraged to activate their driving automation systems but being aware if any takeover request or disengagement appears.
D	The road segment presents fair compatibility with some ODDs. Drivers of level 4 and level 3 vehicles may activate their systems, being aware of the road and traffic conditions. Drivers of level 2 vehicles are discouraged from doing so.
E	The road segment presents nearly null compatibility with most automation systems. Drivers should perform in manual mode.
Note: please see Table 2 in the Document to see which factors are used to determine the LOSAD.	

An Operational Design Domain (ODD) refers to 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. Therefore, an ODD can be defined as a road section that meets some characteristics that allow a driving automation system to perform.

Within a certain road segment, the different vehicles will present specific ODD-compliant sections. The zones that are ODD-compliant to all vehicles are indeed sections that can be driven autonomously by all vehicles. Knowing this information is very important for Road Administrations and Operators, since they could actively work towards increasing their length and adapting new sections. These sections are proposed to be called Operational Road Sections (ORS).

Finally, it is important to introduce the concept of disengagement and takeover request. A disengagement takes place when a driving automation system cannot keep the control of the vehicle and releases it to the driver in an unplanned manner. These events are common to level 2 vehicles and may take place even within ODD-compliant road segments.

Level 3 and level 4 vehicles are technologically more robust, being able to foresee when the driving automation system would stop performing the Driving Dynamic Task. Instead of instantly releasing control to the driver, these can request the human driver to intervene (takeover request). This may happen to level 3 vehicles even within an ODD-compliant section, which cannot happen to level 4 ones.

Infrastructure Support for Autonomous Driving (ISAD)

An adequate connectivity and digital information are key to share information to connected vehicles. The ISAD parameter can be used to rank how road segments provide this service. Like LOSAD, it presents five levels, as follows:

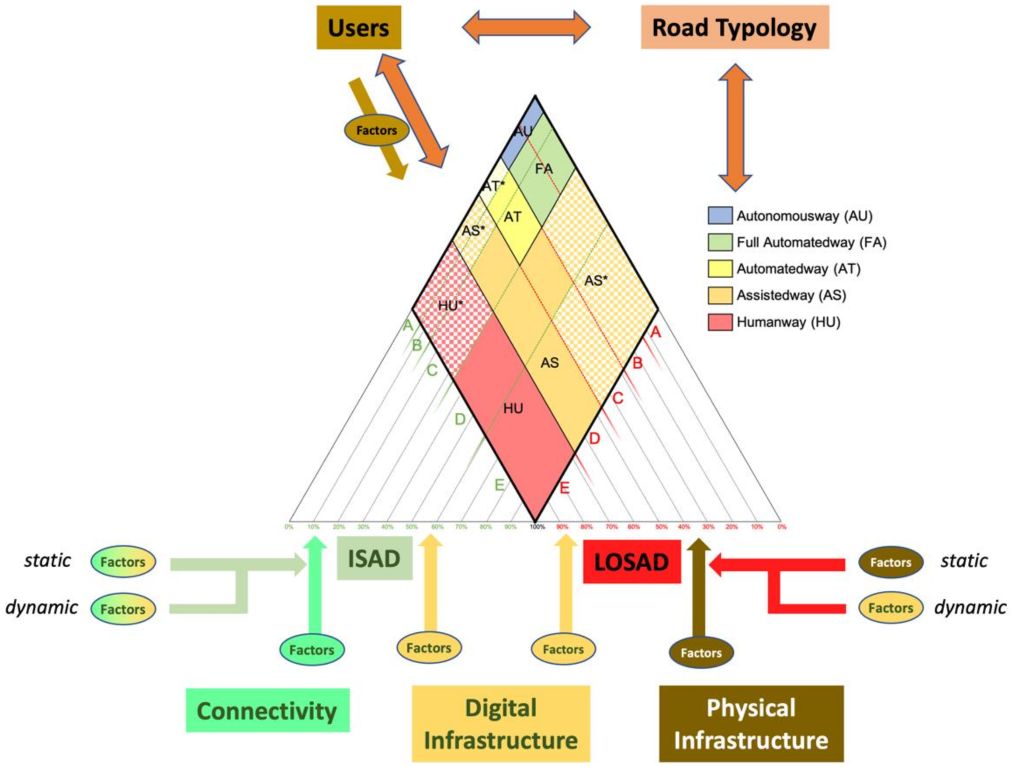
A	The road segment supports cooperative driving: the infrastructure can perceive information and give orders to vehicles to improve safety and traffic operation.
B	The road segment supports cooperative perception: vehicles can inform the infrastructure through V2I about microscopic traffic and road conditions.
C	Digital information about the road segment is available (such as HD maps). Dynamic information (e.g., signs, weather, etc.) is regularly updated.
D	Static digital information available. This information is not updated in real time.
E	Conventional infrastructure with no digital support.
Note: please see Table 3 in the Document to see which factors are used to determine the ISAD.	

Smart Roads Classification Levels

A road segment may present particular support capabilities to host Connected and Automated Vehicles (CAVs), which can be determined with the interaction of LOSAD and ISAD levels. The five road smart levels are as follows (from worst to best support):

HU	**Humanway**. The road segment is not ready to host CAVs, due to the high number of disengagements, and/or the low capability to share digital data to inform vehicles about their ODDs.
AS	**Assistedway**. The road segment is adequate to perform autonomously, but this condition may stop due to different factors (not as frequently as HU segments). Therefore, drivers of automation levels 1 to 4 vehicles should be attentive to the road to disengagements or takeover requests.
AT	**Automated way**. The road segment presents reasonably good connectivity and physical infrastructure capabilities, so disengagements or takeover requests would be quite lower compared to AS and HU. Vehicles can match their ODD limitations with the digital information shared by the road segments, so most takeover requests (levels 3-4) are planned.
FA	**Full Automated way**. The road presents a continuous ORS, ensuring ODD compatibility with far most level 3-4 vehicles. Digital information is shared, so these vehicles can plan any takeover request. Therefore, an experience without disengagements can be attained. Level 2 vehicles would experience very low number of disengagements.
AU	**Autonomous way** . Similar than FA, the connectivity infrastructure supports cooperative driving, so the infrastructure can receive and transmit tailored instructions to all vehicles, micromanaging traffic performance. This road segment type is exclusive for level 4-5 CAVs. This highest smart level may be designated to some lanes.

The following figure clarifies which LOSAD/ISAD combinations are behind each Smart Road Level. Some slight differences may exist within every single level, without compromising the description mentioned above. Some LOSAD/ISAD combinations are not recommended and have been cleared with a white pattern. The diamond shape aims at emphasizing the bottom-to-top path that a road segment would follow in order to improve its SRC level.



Note: to facilitate application by Road Administrations and Operators, as well as interpretation by vehicle manufacturers, a detailed approach to the same SRC levels is given, by making all underlying LOSAD and ISAD factors explicit (named as **detailed classification system**, Tables 7 to 11 in the Document).

Possible Applications

There are many applications of the SRC framework, either by itself or combined with other classification systems. Connectivity of vehicles and their interaction to other vehicles and the infrastructure would dramatically change, opening the floor to new services and stakeholders. Some of these possible applications are drafted as follows, but others remain unknown to date. The intention of Questionnaire 3 is also to obtain feedback on these possible new uses.

Road Administrations and Road Operators

Currently, there is a high variability of the roles of Road Administrations (RAs) and Road Operators (ROs), depending on the country. Tasks can be grouped in two main areas:

- Planning and investment. In this area, RAs and ROs would be responsible of determining the SRC level of their road segments, either by means of LOSAD/ISAD or through the detailed classification system. With it, investments could be planned in order to maximize the number of users benefited with higher SRC levels.
- Management. ROs would be responsible for monitoring how vehicles perform throughout their road network. In combination with RAs, they could also decide about the specific thresholds for the dynamic factors of the SRC levels.

These decisions are extremely dependent on the information provided by vehicle manufacturers – such as explicit ODDs or disengagements. This information is not available nowadays, so how RAs and ROs use the SRC will differ in time, as explained below.

Short-term

Nowadays, driving automation system levels 4-5 do not exist, and level 3 are starting to appear. The digital infrastructure and connectivity factors are still in an early stage of development. Therefore, **AT**, **FA** and **AU** road segments cannot be delimited and would not have any significant impact.

RAs should therefore only focus on determining and physically delimiting **AS** road segments. Users of SAE levels 2-3 vehicles would then know where it is recommended to activate the automation assistance. The thresholds to identify these road segments should be obtained from literature, provided that explicit ODDs and information about disengagements will presumably not be available.

Mid- and long-term

In a mid-to-long term, explicit information about ODDs and/or disengagements is expected to be available. With it, researchers, RAs and ROs could better decide which thresholds are recommended for the different SRC levels.

LOSAD and ISAD could be used by RAs and ROs in order to automatically determine the support of their road networks for CAVs – e.g., using GIS-based tools. This would help in deciding where and when would optimize the outcome of their investments.

When level 4 vehicles become a reality – even for very specific conditions – RAs and ROs could decide the optimal distribution of **FA** and **AU** road segments.

Traffic performance and safety monitoring would also become of major importance, giving valuable information about the impact of higher SRC levels that could be used for planning, or dynamically deciding when the SRC level of a road segment must change.

Some key performance indicators (KPIs) have been proposed to know the performance situation of the road network and make strategic decisions, maximizing the outcome of investments. The KPIs can also be used to compare the situation of a road network longitudinally (i.e., in time) and to the road networks of other countries or regions.

Users

Users are the ultimate and most important target of the SRC system. The goal is that they receive very clear information regarding whether to activate the system or not. Like for RAs and ROs, this is fully dependent on the timeframe.

Short-term

In a short-term, many drivers are unfamiliar with Automated Vehicles – some of them even reluctant to using them. Without the SRC, drivers of levels 2-3 vehicles are using automation assistance with a variety of outcomes. At high-end roads, these systems work well but driver should know that they must be attentive to the road to takeover when disengagements appear. At other roads, drivers might experience far-from-comfortable driving due to very frequent disengagements.

By delimiting the **AS** segments, this situation would presumably change since drivers would be physically informed about where automation is recommended (they would always be reminded about the necessity of staying aware of the road since disengagements would still exist). When entering a road segment without this indication, drivers would know that driving assistance is not encouraged. This would work on safety and user acceptance.

Mid- and long-term

In more distant scenarios, physical and digital signs would exist for all different SRC levels. Level 2-3 drivers should always be attentive to the road to react to disengagements – although a lower number of them would be expected with higher SRC levels. Level 4 vehicles could operate fully autonomously when entering FA and AU road segments, and with a very low number of disengagements at AS and AT.

Vehicle manufacturers

Nowadays, vehicle manufacturers invest enormous amount of money in research driving automation systems. Their objective is to maximize the environments where these systems can perform. However, there is a lack of specific regulations about this performance. While level 2 driving automation systems can basically rely on sensor-captured information, higher levels of automation would require information about the road infrastructure, environment, safe harbors, etc. to match with the systems' ODDs. This is particularly important for level 3 vehicles, for which the road digital information can provide a very important extra time for the driver in order to respond to takeover requests.

Therefore, a tight connection between vehicle manufacturers, road infrastructure and connectivity providers should be established, defining which information would be valuable for manufacturers to expand their ODDs. An open and comprehensive ODD taxonomy would help vehicle manufacturers to express their operational conditions, this being the basis of Operational Road Sections. This connection can also be perfectly seen at AU road segments and connectivity-based intersection optimization.

Other stakeholders

New services and business opportunities will appear in the future, both private and public. HD map providers could match the specific road circumstances with every single ODD, providing tailored information to drivers and CAVs or foreseeing possible disengagements sooner.

By using the sensors of vehicles and connectivity, information about traffic and pavement condition could also be retrieved and transmitted to Road Administrations and Operators or Traffic Management Centers for multiple purposes, such as supporting road maintenance, exploitation, or inform the final users about road events.

Conclusions

As Automated Vehicles become more common in our road networks, it seems necessary to define how these should interact with the road infrastructure. On the one hand, drivers of low automated systems should have clear indications about where they could activate their systems in a confident and safe way. On the other hand, higher levels of automation would be really benefited from digital information coming from the infrastructure and environment, complementing data that can be perceived by vehicle sensors. This would be especially beneficial to the safe and fast deployment of level 4 vehicles.

In both cases, a Smart Roads Classification Framework could help all stakeholders and users to know what they can provide and expect from the road infrastructure. This framework is far from being fully detailed, which is something that will come in the near future as technology evolves, standards are defined, road infrastructure is adapted, connectivity facilities are deployed and users become familiar with CAVs.

A1.2 Extended document

1. Introduction

1.1. Background

Traditionally, road network classification systems have focused on two fundamental opposite dimensions: mobility and accessibility. Since its inception, these classification systems have evolved with the intention of adapting to the new circumstances of society. This is the case of the Expanded Functional Classification System [1] proposed recently in the United States to integrate the different types of users.

However, none of these classification systems considers the incipient appearance of Connected and Automated Vehicles (CAVs) on our roads, so a new Smart Roads Classification system for the road network is therefore required. In this context, two research projects have recently finished integrating the particularities of CAVs in road classification: Connected Roadway Classification System [2] and INFRAMIX [3]. The first one established a road classification based on three approaches: talking (vehicle-infrastructure communication), seeing (infrastructure readability), and simplifying (design and operations for automated vehicles); whereas the second one proposed a road classification focusing mainly on vehicle-infrastructure connectivity.

Existing Automated Vehicles consist of diverse Advanced Driver Assistance Systems (ADAS) that allow an automated driving experience under specific circumstances. Their role in the driving task has become so important that the Society of Automotive Engineers (SAE) proposed a 6-level classification of automation based on how human and vehicle share the driving task [4].

Despite the great effort of the automotive industry during the last decade, the most advanced systems nowadays are level 2 (3 at the most). Such driving automation system is not able to adapt to all circumstances that may arise along a road. An unexpected event triggers the system to transfer control to the driver. These control transfers could become an important safety weakness because of the unexpected event they produce in the driver. This issue increases as control transfers become less frequent, which means that, paradoxically, a system that generates fewer transfers of control might have worse consequences from a road safety perspective. In contrast, in sections with very frequent control transfers, drivers will probably end up switching off the system for their comfort. The frequency of control transfers depends on the system technology as well as the infrastructure and environment. In general, smoother road alignments tend to produce fewer transfers of control [5] [6] [7] [8] [9] [10].

To enable and promote a quick and reliable generalization of Automated Vehicles, users need to trust in their capabilities. A driver should not voluntarily decide whether to connect the assistances, but rather by having objective information about its operation along the segment to be travelled. This information must be provided by combining the characteristics of the infrastructure and the driving automation system.

In addition to the development of automated vehicles, there is also a boost in making use of connectivity and information-sharing to further enhance traffic operation and safety [11]. Vehicle to X (V2X) refers to an intelligent transportation environment where all vehicles, users, and infrastructure systems are interconnected. Connecting all elements – vehicles, road users, infrastructure, traffic, and weather data, and so on – will lead to more accurate knowledge of traffic situation across the road network, which in turn will help improve traffic operation, reduce road crashes, and minimize vehicle emissions.

Besides communication between vehicles (V2V), connectivity between vehicles and infrastructure (V2I) comes into play. This protocol will allow vehicles to interpret traffic signals and know who has priority in certain critical situations. Likewise, CAVs will be able to know the ideal route at all times as they will know the status of traffic in real time thanks to Vehicle to Network (V2N) technologies. Furthermore, since they are not on their own, Vehicle to Pedestrian (V2P) communication is also being developed to alert the presence of vulnerable users. Different technologies are being developed and deployed such as Roadside Units (RSUs) equipped with DSRC/WAVE and ITS-G5 or Cellular V2X (C-V2X) solutions based on the last releases of 4G and/or 5G technology at some urban zones and along main highways.

Automated and connected driving goes hand in hand with different political objectives that the European Commission, the United States, United Kingdom, and China has been pursuing for years. For this, the new

CAVs must be integrated into the transport system, which requires the joint work of all agents involved. As a result, an adequate legal and political framework is expected that encourages mobility and automated driving.

1.2. Objectives

This Special Project aims at exploring the feasibility of a new framework for the classification of the road infrastructure. This framework is based on the road physical and digital characteristics and the hosting capacity of connected and automated vehicles.

Given that the presence of Connected and Automated Vehicles (CAVs) is on the increase, it is necessary to explore a new Smart Roads Classification (SRC) system that could provide information to users and vehicles on their degree of adaptation to automated and/or connected driving. This information should range from indicating which road sections do not allow any type of autonomous driving, to sections that are ready for any autonomous system, going through various intermediate degrees depending on the technology. Additionally, the system should consider information about the connectivity capabilities.

An integral road classification system would also allow an efficient planning of public investments on physical infrastructure, by enhancing operativity of driving automation, and on digital infrastructure, by increasing the benefits of connectivity between highways and their users (V2X). End users will be informed about the level of automation they can enable through each road segment. Consequently, a safer, more sustainable and comfortable road network is expected.

This system should be based on existing autonomous driving and connectivity technologies and be highly resilient, so it could be quickly adapted to the technology progress, research findings, and best practices. It should also be compatible with existing road classification systems and the coexistence with other human-driven vehicles and users.

The new classification system should be universal – i.e., applicable to roads worldwide –, and agreed upon, to enable a simple-to-use and rapid-to-implement tool. In this way, the SRC would allow road decision makers the planification and prioritization of investment needs in physical and digital infrastructure, including no-regret measures, to progressively expand and encourage an automated and connected driving.

Summarizing, the SRC should fulfill the following objectives:

- Common language, to facilitate communication between all stakeholders;
- Useful, to facilitate the application by Road Administrations or road operators;
- Universal, to be applicable to roads worldwide and to all types of roads;
- Standardized, to ease its development and implementation;
- Interoperable, to facilitate data exchange;
- Robust, to provide an adequate and coherent smart level for every road segment;
- Consistent, to facilitate adequate messages for users;
- Simple, to ensure understanding for users;
- Integrable, to facilitate the necessary transition from the current classification systems;
- Dynamic, to reduce the assigned intelligent level after sudden variations in environmental and operational factors;
- Flexible, to be quickly and easily adaptable to technological advances and sudden variations in technology operation; and,
- No liability for road administrations or road operators.

2. Literature Review

This section contains the main findings and conclusions of the impact of automated driving at the infrastructure level which can be grouped into the following categories: (i) impact of automated driving on road classification systems; (ii) current automated driving limitations; (iii) role of connectivity in automated driving; (iv) definition of key concepts linked to automated driving; and (v) the implications of automated driving on safety.

First approaches on **road classification systems** were focused on motorized vehicles driven by humans. In the last decade, some road administrations have incorporated vulnerable users, such as cyclists and pedestrians, in the classification of the road network [1]. However, this is not enough as automated vehicles already are a reality in our roads.

To address the integration of CAVs in road classification systems, some efforts have been carried out in the last years that include different approaches [2] [12] [13] [14]. The Connected Roadway Classification System (CRCS), based on three main approaches – talking, seeing, and simplifying –, can be very practical for road administrations and operators to allocate investments, but not for road users as the classification system does not stablish clear road levels [2]. To this regard, the proposed classification system defines the attributes or conditions to be gathered in each road level but does not specify the thresholds for these attributes. Therefore, the application of the system requires of further development.

The ISAD levels proposed in the INFRAMIX project [12] add a critical aspect for automation – especially the highest levels –. However, connectivity is not sufficient on its own to define how ready a road section is to host automation. For instance, smooth alignments with weak connectivity are likely to be more drivable by automated vehicles than low-end ones – winding roads – with magnificent connectivity conditions.

Despite the benefits, these levels still require to be completed with additional information to be fully adopted by road administrations and operators. This information includes, but it is not limited to, the accuracy of the maps at the different levels, the update rate of the static information, communication capacity and protocols to/from vehicles, and so on.

The classification system proposed by the EAPA [13] relies on connectivity and vehicle capabilities. In this way, six road classes are defined depending on the ISAD levels [12] and SAE levels of automation [4]. Additionally, the classes are complemented with a number of stars that indicates the integration of electric vehicles (EVs). Despite the inclusion of some key parameters associated with the infrastructure – road marking, signs, and pavement condition –, other important factors – e.g., road geometric design – are not considered. Thus, this classification system underestimates some essential factors that present a great influence on CAVs performance.

Finally, the Autonomous Vehicles Readiness Index (AVRI) includes issues or items not considered by the previous systems such as Consumer acceptance and Policies and regulations [14]. These items together with Infrastructure and Technology and innovation are the four pillars that define the level of automation of a country at a macro level. The AVRI cannot properly reflect the degree to which a road network is enabling an automated driving because of its definition. In fact, the infrastructure pillar is mainly based on items related to connectivity, disregarding physical infrastructure features.

In short, the proposed classification systems integrating CAV particularities are based on diverse approaches and, therefore, a harmonization is needed. Although policies and regulations are needed to boost the use of CAVs and consumer acceptance is crucial to increase CAV sales, the level of automation of a road must not depend on these issues. On the other hand, most of criteria included in existing classification systems are not associated with thresholds and key performance indicators, making the implementation of these systems harder. Last but not least, none of existing systems integrate dynamic conditions of the road – e.g., traffic volume or weather conditions – to determine the capability that a road has to enable an automated driving.

Although vehicle technology is constantly enhancing and evolving, the sensors and algorithms included in CAVs cannot cope with specific **challenging situations**. Demanding road geometry – sharp horizontal and vertical curves and narrow lanes – usually leads to vehicle system disengagements. In addition, diverse research found 150 mm width and 150 mcd/m2/lx retroreflectivity road markings ease CAVs operation. In this way, high-capacity roads – freeways, expressways, and motorways – are already ready to integrate CAVs as their features encourage road readability and connectivity. In addition, this road category opens up the creation of dedicated lanes (DLs).

Most Traffic Sign Recognition (TSR) systems recognize only posted speed limits and priority of way signs such as STOP or yield. Nevertheless, the performance of these systems depends on the position – up to transverse distances of 10 m – and orientation – up to 45° perpendicularly to the road – of the traffic signs. Other critical aspects are the maintenance of traffic signs and the environmental lighting as the accuracy of TSR systems decreases with a poor maintenance and in situations of low or altered lightness. Furthermore, Variable Message Signs present additional limitations linked to the intrinsic aspects to this technology: (i) contrast and adaptability to surrounding light; (ii) interpretation of LEDs to form characters and pictogram; and (iii) image flickering.

Despite the few studies quantifying the influence of pavement condition on CAVs performance, it is clear that the state of the pavement surface plays a critical role in automated driving. To this regard, the new road classifications that include the particularities of these type of vehicles agree with a good pavement condition is needed to achieve the highest levels of automation.

The main environmental factors affecting CAVs performance are weather and lighting. Unfavorable weather conditions – heavy rain and fog – makes road marking and traffic sign recognition very difficult as these tasks are carried out by vision cameras that are very sensitive to visibility. Related to this, street lighting and tunnels can also influence the performance of CAVs. An improvement of street lighting, in terms of better illumination or more closely spaced lights, may be required to ensure that the visibility of road markings, signals, and signs is suitable for an effective CAVs performance. Furthermore, tunnels are linked to two important issues: (i) sudden changes in illumination conditions and (ii) low Global Navigation Satellite System (GNNS) signal coverage. Although some innovation solutions have been proposed to deal with both issues, further research is needed to stablish standardized solutions and consistent with automated vehicles' capabilities.

Many car manufacturers are developing safety and communication systems to avoid collisions with non-motorized vehicles, such as pedestrians and cyclists. However, current interaction patterns and strategies cannot be automatically transferred to a situation with automated vehicles or to a situation with vehicles with different levels of automation. Above all, pedestrian and cyclist behavior are often unpredictable.

In addition to above-mentioned shortcomings or limitations, it should be noted that speed is a critical factor in road marking recognition because information processing must be faster as the vehicle speed increases. Related to this phenomenon, the **Automated Speed** was defined as the maximum speed that an automated vehicle can achieved at a specific road geometric element. Furthermore, Advanced Driver Assistance Systems are usually limited to specific range of speeds. Adaptive Cruise Control (ACC) usually works from 30 km/h, while Lane Keeping and Centering Assist (LKA and LCA) work when the vehicle speed is over 60 km/h.

Another of the most important challenges concerning automated driving is **connectivity**. Vehicle to Everything (V2X) is a communication system which interconnects a road vehicle to any entity that may concern it. To this regard, V2X encompasses a range of communications channels, including:

- Vehicle to Vehicle (V2V): Direct communication between two vehicles.
- Vehicle to Infrastructure (V2I): Communication between a vehicle and fixed infrastructure, such as traffic lights, infrastructure monitoring and control devices, parking services, etc.
- Vehicle to Pedestrians (V2P): Communication between vehicles and pedestrian devices, alerting pedestrians of vehicle movements and warnings for vehicles.

- Vehicle to Device (V2D): Communication between vehicles and non-V2V enabled vehicles and cyclists.
- Vehicle to Network (V2N): Communications with the cellular network, either to facilitate other types of V2X communications or to access internet resources.

Currently, there are two V2X communication approaches using different underlying technologies. While the IEEE's approach is Dedicated Short-Range Communications (DSRC), which supports vehicular ad-hoc connectivity WLAN technologies standardized as IEEE 802.11p [15] – known in America as WAVE and in Europe as ITS-G5 –, the 3GPP's approach is based on Long Term Evolution (LTE), which consists of cellular technologies (C-V2X) [16].

Roadside Units (RSUs) are using DSRC communications and need the vehicle speed be relatively low for switching. However, recent C-V2X communications based on 5G New Radio have emerged as a complementary access technology in order to provide sophisticated applications and use cases with more stringent Quality of Service (QoS) requirements – e.g., platooning or advanced driving –.

Highly automated vehicles need to monitor everything taking place on the route ahead, even beyond the range of their sensors. Connected and automated vehicles with their sophisticated sensing systems are also part of the solution, but the quality of traffic information needs to be improved. To this regard, CAVs need basically two types of information systems: (i) real-time information and (ii) rules and regulations of any restrictions ahead. Therefore, a highly versatile framework that supports several wireless technologies is needed, especially to allow high-level automation. For that purpose, a strong cooperation between all stakeholders is mandatory.

Moreover, it is important to distinguish between the **key concepts** of Operational Design Domain (ODD), Operational Road Section (ORS), Level of Service of Automated Driving (LOSAD) [6], and Infrastructure Support Levels for Automated Driving (ISAD) [3].

According to the SAE J3016, an **Operational Design Domain (ODD)** refers to 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" [4]. Therefore, an Operational Design Domain can be defined as a road section that meets some characteristics that allow the driving automation system to perform. Many of these characteristics refer to the roadway type, road infrastructure, some others refer to the environment, traffic conditions, maximum speed attainable by the driving automation system, etc. These factors also involve variable – i.e., non-static – parameters. Given the early stage of ODDs awareness and implementation by industry, it might be easier to define them by referring to the limitations, i.e., the conditions that are out the ODD.

To foster the expansion and implementation of ODDs, it is necessary to give a better, more detailed compendium of all parameters and thresholds that might intervene, i.e., a taxonomy. There have been recent efforts in that direction. A first official approach for ODD taxonomy was introduced by the British Standard Institution (BSI), which considered three main attributes: (i) scenery, (ii) environmental conditions, and (iii) dynamic elements [17]. The European ITS Platform (EU EIP) [18] developed another taxonomy, differentiating between (i) physical infrastructure, (ii) digital infrastructure, (iii) communication infrastructure, and (iv) infrastructure operations and maintenance. In 2020, the Society of Automotive Engineers (SAE) released a report with a conceptual framework of ODDs [19]. This framework focuses on the physical road infrastructure including its geometry, the environment, and the behavior of other road users. OEMs are encouraged to explicit and make public the factors supporting/limiting their ODDs. The following factors are proposed: (i) weather- and climate-related environmental conditions, (ii) surface road conditions, (iii) operational restrictions, i.e., other aspects within the operational environment not related to the first category, (iv) road users, (v) non-static obstacles on the road, (vi) connectivity to other road users, infrastructure, and traffic management centers. The most remarkable limitation to ODDs is that these have been defined from the point of view of the vehicle, and every single vehicle (or model) will have its unique – and time varying – ODD. Therefore, a road segment being drivable by an automated vehicle is not a property given or managed by the road administration or operator, but a varying characteristic of every single automated vehicle.

The lack of a standardized definition of ODD hinders OEMs to explicit their ODD constraints. In the end, this makes it more difficult for road administrators to be aware of which road segments are more adequate for automation.

In addition to the elements that an ODD taxonomy should include, thresholds for these elements should be applied too (e.g., minimum radius compatible with automation for a certain speed; minimum road marking width, etc.). These thresholds should be robust, i.e., they should ensure that a vehicle lying within the ODD range would not release control triggered by this factor.

Establishing clear ODDs is especially important for SAE levels 3 and 4. For lower levels, the driver is the one responsible for all the Driving Task, given the relatively frequent disengagements. Level 5 is the top level, a vehicle capable of driving anywhere regardless ODDs.

To facilitate the application and management of ODDs from the road infrastructure side, it is necessary to generalize the concept to a traffic stream with vehicles showing different automation capabilities. Within a certain road segment, the different vehicles will present specific ODD-compliant sections, generated by different factors. The zones that are ODD-compliant to all vehicles are indeed sections that can be driven autonomously by all vehicles. Knowing this information is very important for road administrations and operators, since they could actively work towards increasing their length and adapting new sections.

These sections are proposed to be called **Operational Road Sections (ORS)**. From a practical perspective, an ORS should be established in all zones that match with all vehicles' driving automation systems. It should be noted that these ODDs should be robust enough to prevent disengagements if some of the dynamic factors slightly vary (i.e., ORS should be as static as possible). By making ODDs explicit, ORS would be easier identified, and OEMs could receive feedback from road administrations to improve their systems.

ORSs, like ODDs, will vary in time. At the beginning, only smooth sections at freeways are expected to be supported by all driving automation systems. As the technology evolves, other sections will become compatible with all systems, extending the ORS application. Active adaptation of road sections would accelerate this ORS generalization, but to select the most cost/effective measures, ODDs should be made explicit.

The ODD may terminate at some point, either in a planned way (the vehicle reaches an ODD physical boundary) or abruptly (some factor exits the safe zone and terminates the ODD). In both cases the vehicle might be capable of performing a Dynamic Driving Task (DDT) fallback, which is not a regular DDT but provides some capabilities to take the vehicle to a safe stop. This situation is called a "Restricted Operational Domain" (ROD).

For every single vehicle, the ODD-compliant sections along a road itinerary are expected to be discontinuous. For SAE levels 3 and 4, the driver is expected to be able to shift to a secondary task while the vehicle is in charge of the DDT. A problem may arise under three circumstances: (i) the vehicle experiments a failure that stops automation abruptly, (ii) the Automated Driving System (ADS) fails, and (iii) the ODD approaches to its end, which is already known by the driving automation system. On the contrary to previous situations, the vehicle has more time to plan how to perform and warn the driver.

In all these cases, the Dynamic Driving Task has to be released to the human driver, who might be attentive to a secondary task. Hence, the ideal situation is a planned handover. Nevertheless, if the driver is unable to take over control of the vehicle, Level 4 and level 5 ADSs can take the vehicle to a Minimal Risk Condition (MRC), which is defined as “a condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be completed”. This means that these highly automated ADSs can still control the vehicle with restricted conditions, make a decision and take the vehicle to a position that minimizes the risk to itself and the rest of road users.

A MRC is a final state, i.e., the objective to reach by the ADS when needed. From the regular performance to the MRC, a maneuver has to be undertook – Minimal Risk Maneuver (MRM) –, which should also be considered to minimize the risk condition. In fact, the ADS may balance several options with diverse risk conditions, finally performing the one that presents the lowest risk in combination with the maneuvers [20].

Comparing road sections with disengagement patterns is especially relevant in order to verify to what extent the proposed ODDs are robust and match the definitions provided by OEMs. Road administrations and operators could also use this information to determine and check their ORSs; and provide newer ones.

It is important to highlight that the driver – either human or vehicle – is the ultimate responsible for the driving task. Therefore, road administrations and operators should make explicit the available automated vehicle supporting road characteristics for every road segment and the automated vehicle will decide if it can switch on automated driving or not, according to the technologies it is equipped with.

The **Level of Service for Automated Driving (LOSAD)** is a concept recently introduced by García et al. [6] to indicate how ready a road segment is to host automation. Like any other Level of Service (LOS), it ranks the road segment from E – minimal automation support – to A – automation fully supported –. Having such a direct indicator to reflect the automated-readiness level is very important for road administrations and operators. Road networks could be ranked as a function of LOSAD. Traffic volume could also be compared to it. These charts could be used to prioritize actions and/or assess the status of a road network. In fact, the LOSAD A road segments would be those identified above as Operational Road Sections – i.e., road sections that are fully compatible with automation – for a sufficient road segment length (thresholds still to be determined).

LOSAD B to E present different extensions and frequencies of ORSs. For instance, LOSAD B may be a segment that presents relatively long ORSs interrupted with a few non-ODD compliant zones for some of the automated vehicles. LOSAD E may be the case of very short ORSs that almost prevent enabling automation. Thresholds and specific characteristics of every level are still to be determined.

Since LOSAD should be based on Operational Road Sections, a very deep knowledge about factors affecting ODDs is required. Otherwise, ODDs should be evaluated for every single vehicle and finally aggregated for the whole road segment. Figure 1 shows how the LOSAD could be determined for a single vehicle. The lower part of the figure represents the engagement (green) and disengagement zones (red) for a given driving automation system. This could be transformed into a time-space diagram (top), computing how frequent these disengagements are.

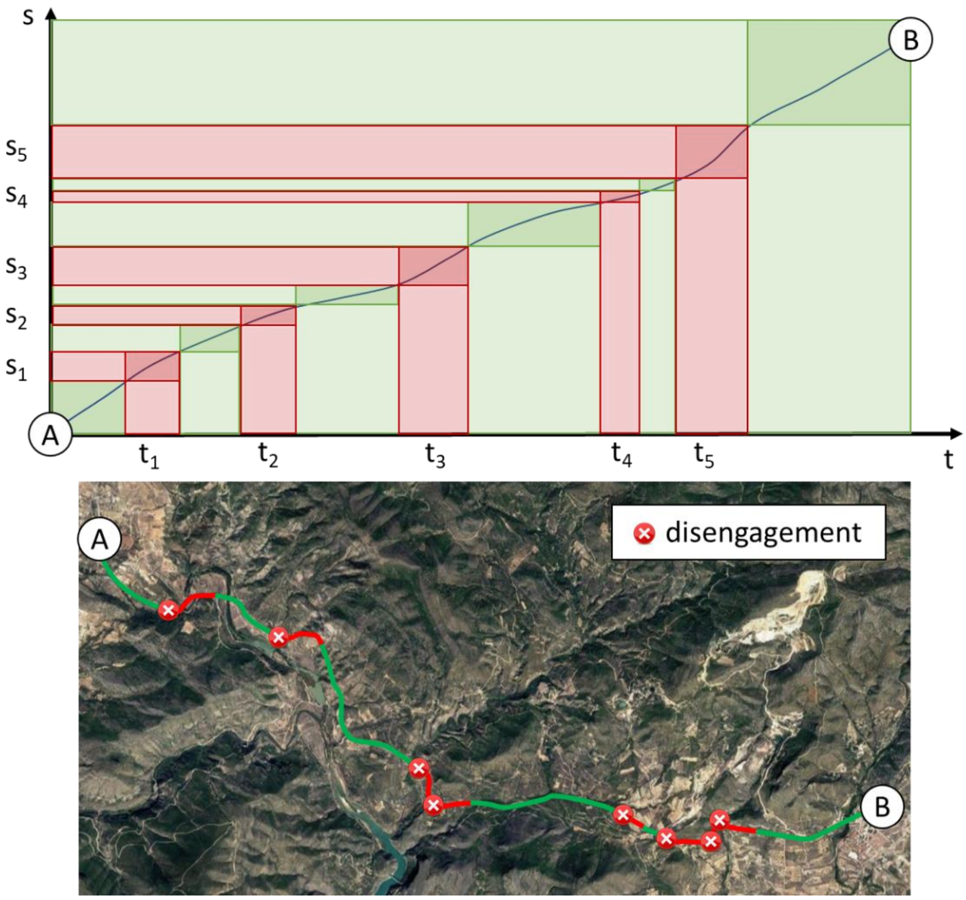


Figure 1. Concepts of ODD and LOSAD.

Another indirect way of determining the LOSAD might be through disengagement reports from marketed vehicles. By geotagging all disengagements – and, if possible, the triggering conditions – HD maps could continuously be updated in order to indicate which road segments are more likely to disengage certain driving automation systems.

The LOSAD concept, despite still requiring further refinements upon the information that finally becomes available, is a complementary parameter to the **Infrastructure Support Levels for Automated Driving (ISAD)** [3]. Like LOSAD, the ISAD is categorized in five levels (A-E), being A the highest connectivity support level, to E (conventional infrastructure). LOSAD describing how vehicles' ODDs interact with the road infrastructure, and ISAD indicating the connectivity capabilities, establish a sound basis to foresee how Connected and Automated Vehicles are likely to perform along a road network.

The **implications of automated driving on safety** can be analyzed at diverse levels – (i) vehicle; (ii) transportation system; and (iii) society – and quantified by means of different approaches – (i) target crash population; (ii) road test data analysis; (ii) traffic simulations; (iii) driving simulators; (iv) system failure risk assessment; and (vi) CAV safety effectiveness – [21]. At a vehicle level, CAVs can be examined by means of their contribution to the critical driver-related reasons for crashes, such as distractions, inattention, or performance error. At a transportation system level, a reduction in the number of traffic conflicts and crashes is expected with the integration of CAVs. At a society level, crashes are one of the main health concerns and the health impacts of CAVs can be studied by comparing crash occurrence under different Penetration Market Rates (PMR), including the scenario only with human-driven vehicles. Obviously, these safety implications depend on the automation levels of the CAVs available on the market.

3. SRC Framework

The Smart Roads Classification framework aims at providing a powerful but easy-to-use tool to determine the smart level of a road segment, based on the LOSAD and ISAD indicators. Therefore, a Road Administration or Road Operator could use these classifications to rank their road networks, compare regions, plan new actions, and so on. This is called the **main classification system** and will be developed in section 3.1. SRC Proposal.

However, for management purposes, the LOSAD/ISAD-based classification may not be the best option since it requires determining both indicators first. This is why all different, underlying factors related to LOSAD and ISAD have been in-depth developed in section 3.2. Factors. These ones constitute a sort of checklist that could be used by Road Administrators and Operators to determine the smart level of their road segments (see A2. Factors). This has been named as **detailed classification system**.

It is important to highlight that both the main and the detailed classification systems correspond to the same framework, only differing in the way they are applied. Moreover, in the section 3.3. Key Performance Indicators, some KPIs have been proposed to assess the evolution of the SRC application along time.

3.1. SRC Proposal

The Smart Roads Classification will be based on two indicators of autonomous performance and connectivity support: LOSAD and ISAD. Both of them are based on explicit indicators that could be retrieved by Road Administrations (RAs). The indicator for the automation level is the **L**evel **O**f **S**ervice for **A**utomated **D**riving (**LOSAD**), proposed by HERG [6], while the indicator for the connectivity level is the **I**nfrastructure **S**upport Levels for **A**utomated **D**riving (ISAD), proposed in the INFRAMIX project [12].

The proposed LOSAD is categorized in five levels, from A to E. It is determined as a function of how ready the road infrastructure is to support automated driving. The most important parameter to define the LOSAD of a road segment is the distribution of their Operational Road Sections. As seen in 2. Literature Review, an Operational Road Section (ORS) can be defined as a section that fully supports automation for all driving automation systems with explicit ODDs. In other words, a section that should be ideally driven by any driving automation system. According to the SAE definition for the different levels of automation, a disengagement-free trip can only be ensured for level 4 (within their ODD sections) and for level 5. Levels 1 to 3 may present disengagements even within their ODDs, so disengagement-free trips can never be ensured.

Before addressing the LOSAD concept, it is necessary to clarify what road segments and sections are in these definitions. A road segment is the road portion delimited by major intersections or an urban environment. Driveways and minor intersections may or may not suppose a road segment change. A road section refers to the minimal portion of the road that presents identical factors, including geometry, cross section, environment, and the like. Every horizontal curve – as well as short tangents – should not be divided into different sections. A long tangent may be divided into different sections, if some important property differs on it.

As the percentage of the road segment that does not belong to an ORS increases, LOSAD will decrease given that high automated vehicles will present lower opportunities to drive autonomously. LOSAD also decreases as ORSs become shorter. The following levels are proposed:

- LOSAD A: The road segment presents a continuous ORS that ensures a safe automated driving for high automated vehicles (levels 4-5). Levels 2 and 3 vehicles should perform with minimum disengagements due to their lower technology, i.e., a disengagement-free driving cannot be ensured from the infrastructure side (although their number would be very low or null).
- LOSAD B: Like for LOSAD A, the road segment is composed of a single ORS that must keep in automation all level 4 and level 5 vehicles. However, dynamic conditions such as weather may

temporarily limit the ORS effectiveness. The LOSAD B also appears if the number of disengagements exceeds a given threshold, mostly caused by level 2-3 vehicles.

- LOSAD C-D: These levels are characterized by a non-continuous ORS within the road segment. The final level will depend on the number and length of ORSs along the segment. Most drivers may need to retake manual control of their vehicles at the non-ORSs. A minimum disengagement rate might also be expected within ORS, as for previous levels. In addition, adverse weather conditions might also trigger LOSAD C or LOSAD D conditions. Specific thresholds are still to be researched in the future, depending on how diverse CAVs are, the minimum period of time that would be adequate to be under automatic control, etc.
- LOSAD E: There are no ORSs, or their length is too short to ensure comfortable automated driving. Therefore, most level 3 and 4 drivers might be willing not to activate their systems. Level 2 drivers would not experience any remarkable benefit from lane keeping assistance, given that it would be disengaged most of the time.

The LOSAD classification is dynamic, i.e., a road segment might shift from one level to a lower one depending on dynamic factors such as disengagements and weather conditions. Two examples are given for clarification purposes:

- A LOSAD A road segment might temporarily shift to B if many disengagements are observed within a section, regardless the triggering factor (it may even be unknown). The level of the driving automation systems suffering disengagements is not relevant in this case.
- A LOSAD B road segment might temporarily shift to D if a sudden, violent rainfall takes place. Heavy rain has two effects: (i) creates a layer of water that may affect automation (this also depends on the drainage conditions), and (ii) limits visibility. The limitation of visibility might also be detected using the Visibility factor. These conditions might also trigger a high number of disengagements, which could be detected using the corresponding factor as well.

A new parameter, the disengagement rate, is necessary to apply one of the factors. This can be defined as the number of disengagements within ORSs divided by the volume of automated vehicles. Thus, it is a way of measuring how well the ORSs are performing, and a way to report unexpected or abnormal behavior of the road infrastructure and automated vehicles. If this indicator is finally established, it would be necessary that all automated vehicles reported these events in real time, including position and time. Other data would be helpful in order to identify the triggering cause. Finally, this report should be provided by all vehicles from level 2 to level 5. RAs would then combine data from all vehicles with additional information (e.g., weather, traffic, etc.), obtaining ‘disengagement maps’ for the road network for a variety of situations.

The information from disengagements is considered to be very important, since it reflects how CAVs are performing along the road segment. Unlike establishing LOSAD based on geometric and environmental factors, this parameter would reflect the consequences of unknown factors affecting CAV performance. Not only would this information be useful to more accurately tag the LOSAD of the road segment, but it would also help research to overcome these limitations, and therefore expand ORSs.

Despite these benefits, all level 2+ vehicles should be legally enforced to provide this information, and RAs should support a detailed, continuously updated road HD map. **This is neither the situation nowadays nor it will be in the short-term**. Once that day comes, a strong effort should be made by Road Administrations to establish an effective way to collect it. If this information is not ever published, alternative protocols should be defined to privately or partially collect this data with the same objective.

From now on, LOSAD, ISAD, and SRC factors will be presented in tables, following the color code in Table 1. Green cells indicate a value proposal. Yellow cells indicate that the value should be defined by the road administrator or operator. Red cells indicate that a value should be provided when its effect on automation is better depicted. However, some values have been provided as a reference (TBD: to be determined).

	Proposed value
	To be researched specific thresholds based upon their effect on Automated Driving.
	To be defined by the Road Operator/Administration

Table 1. Color-code for the values provided in LOSAD, ISAD and SRC tables.

Table 2 shows the static and dynamic factors that should be considered to decide the LOSAD level.

Like LOSAD, the **ISAD is categorized in five levels** (A-E), being A the highest connectivity support level, to E (conventional infrastructure). These are the following:

- ISAD A: Support for cooperative driving, in which the infrastructure is fully capable of perceiving the behavior of all vehicles and guiding the traffic to guarantee efficiency and safety.
- ISAD B: Support for cooperative perception, in which the infrastructure can perceive some microscopic traffic situations and communicate with vehicles. There is some level of cooperation but still not with a full range of situations.
- ISAD C: Dynamic digital information, in which the infrastructure can modify the information of road variable message signs depending on weather or incident warnings.
- ISAD D: Static digital information/map support, which means that in this case the infrastructure provider – the road administration or operator – supplies to the vehicles along the area with digital map data complemented by physical reference points.
- ISAD E: Conventional infrastructure with no digital support, referring to today's roads in which there is not any digital infrastructure data and, therefore, no explicit Automated Vehicle support is provided.

These descriptions were introduced by the InfraMIX project [12]. Most of them refer to the data requirements of the digital infrastructure, with lower attention to the physical part of the infrastructure, or the connectivity requirements.

Table 3 presents a compendium of all properties related to the digital infrastructure, and some requirements on the physical and connectivity parts. Some of these factors have been partially adapted from the originals indicated in the InfraMIX project, for clarification purposes. All factors are just suggested, given that these should be detailed by further research and international agreements about the standards. The same colors than for LOSAD apply (Table 1).

Layer	Factor	Type	Domain	Parameter	Description	E	D	C	B	A
Physical Infrastructure	ORS	Static	Road Segment	Number	Number of ORS that should be within a road segment		<=5 (TBD)	<=2 (TBD)	1	1
			Road Segment	% of total length	Percentage of the total length of the road segment that should correspond to an ORS		75% (TBD)	90% (TBD)	100%	100%
Digital Infrastructure			Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])	Maximum allowable disengagement rate within ORSs, per time and length. All SAE levels are considered. Manual requests are not considered.				5 (TBD)	0 (TBD)
	Weather	Dynamic	Road Segment	Visibility (MOR)	Visibility range from weather stations		200 m	500 m	1000 m	1000 m
		Dynamic	Road Segment	Snow/icy pavement	Ice on the pavement may reduce the skid resistance and therefore prevent adequate automation. Snow on the pavement may prevent to distinguish road markings.		Heavy snow	Moderate snow	Light snow	Light snow
		Dynamic	Road section	Rainfall intensity	Rainfall may limit visibility.		Violent rain (<100 mm/h)	Heavy rain (<50 mm/h)	Moderate rain (<7.5 mm/h)	Light rain (<2.5 mm/h)

Layer	Factor		Domain	Parameter	Description	E	D	C	B	A
Digital Infrastructure	Mapping and digital informatio	Static	Road segment	Digital map	Availability of a digital map with static road signs, junctions, etc.		Standard map	HD map	HD map. MRC zones	HD map. MRC zones

Layer	Factor		Domain	Parameter	Description	E	D	C	B	A
	n availability								are included	are included
		Static	Road segment	Digital map update frequency	How frequent are maps updated?		Manually	Automatic, not necessarily real-time	Real-time	Real-time
		Static	Road segment	Road traffic and events ahead	Availability of DIGITAL information related to road traffic and events ahead			Y	Y	Y
		Static	Road segment	Weather conditions	Availability of DIGITAL information related to weather conditions			Y	High precission data with forecasting possibilities	High precission data with forecasting possibilities
		Static	Road section	Variable speed limit	Availability of DIGITAL information related to Variable Speed Limit			Variable Speed Limits are transmitted to vehicles	Variable Speed Limits are transmitted to vehicles	Tailored Speed Advice is transmitted to vehicles
		Static	Road section	Traffic lights	Availability of DIGITAL information related to traffic lights			Y	Y	Y
		Static	Road section	Traffic performance information	Availability of traffic data for management, indications, and other purposes			Macroscopic	Microscopic, obtained from vehicle data	Microscopic, obtained by the road infrastructure
		Static	Subject vehicle	Microscopic dynamic driving guidance	Can the Digital Infrastructure provide tailored instructions in a vehicle-basis? (i.e., cooperative driving)				Speed and lane advice might be sometimes provided	Y
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)	Are there RSUs?				Yes, ensuring I2V	Yes, ensuring V2I and I2V
		Static	Road segment	Sensors for trajectories of vehicles and users	Specific road sensors to detect the trajectories of vehicles/users				Y/N	Y
		Static	Road segment	Automatic road data processing	Can the infrastructure automatically process information from multiple sensors (e.g., in-pavement			Y	Y	Y

Layer	Factor		Domain	Parameter	Description	E	D	C	B	A
					sensors, cameras, ramp metering…)					
		Dynamic	Road Segment	Positioning accuracy	How accurate is the position of vehicles, despite the specific equipment used (RTK land stations or reference points)		Accurate	Very accurate	Highest accuracy	Highest accuracy
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Short range communication			Y/N	Y	Y
	C-V2X (5G)	Static	Road segment	Availability	Cellular V2X (Vehicle-to-Everything) communication			Y/N	Y	Y
	DSRC	Dynamic	Road segment	Range (m)	This range is related to RSUs density			2000	1700	700
	Reliability	Dynamic	Road segment	% Packets received in due time	This is related to signal strength fluctuations			99%	99.90%	100.00%
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)				3	6	30
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	This is a measure of delay			100	40	5
	Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	The average power received from a single Reference signal			-85	-82	-67

Table 3. Factors related to ISAD.

The different LOSAD and ISAD levels provide road segments with different characteristics related to automated and connected driving. Moreover, some interactions of these levels generate synergies that are especially interesting for road authorities and operators to foster.

As a consequence of the various interactions, **five different types of Smart Road segments can be distinguished with specific characteristics related to CAVs**. Although there are 25 possible combinations of the different LOSAD and ISAD levels, some of them are very similar and can be grouped together. From lower to higher CAV support, these five levels are proposed:

1. **Humanway (HU).** The road is not ready for CAVs. This means that level 2-3 vehicles would experience too many disengagements, prompting their drivers to manually disconnect the system. These segments would not present ORSs, and level 4 vehicles may not find clear ODDs – this would depend on the specific technology of the ADS – and will generally perform in manual mode. A level 5 vehicle would be able to operate along this road – provided that these vehicles are ODD-free – but connectivity to infrastructure is not guaranteed. However, even for these high-end vehicles, performance, operation, and safety might be compromised as well, if they cannot operate at a reasonable speed.
2. **Assistedway (AS).** The road is adequate for level 2+ vehicles, meaning that it would not induce too many disengagements to levels 2-3. This would allow drivers to enable their driving automation systems. Road administrations should put special focus on ORS discontinuities and any other disengagement-prone location, to prevent driver distractions, especially for level 3. While more extensive ODDs can be found compared to HU, the road segment might be divided into many ORSs that do not provide a comfortable and automated driving experience for level 4 vehicles, limited by the physical infrastructure or the connectivity capabilities (the road cannot provide detailed information about the dynamic parameters that should be compared to ODDs).
3. **Automated way (AT).** The road segment presents better characteristics than AS segments, especially related to connectivity. These road segments present HD maps and can transmit digital information to CAVs, so these can better identify ODD-related factors and ODD terminals. In addition, less and more continuous ORSs can be found within. Level 2 vehicles would experience less disengagements than on AS segments, and level 3 vehicles would be able to use the digital information to foresee oncoming disengagements. The longer ORSs would allow a better, longer performance of level 4 vehicles in automated mode.
4. **Full Automated way (FA).** The road segment presents a continuous ORS, so all level 4 vehicles should be able to operate autonomously along the entire segment. In addition, these segments present safe harbors – including their junctions to other segments –. While the ORS is not directly related to level 2-3 vehicles – these are not required to explicit their ODDs – a much lower number of disengagements compared to AT is also expected. Connectivity is even better than AT segments, facilitating cooperative perception and including all safe harbors in the HD map. All road users would benefit from better global performance and safety levels.
5. **Autonomous way (AU).** The road segment presents similar physical conditions than the FA segments – i.e., complete ORS along the segment, safe harbors, etc. –, and incorporates exceptional connectivity features that enable cooperative driving. In order to benefit from the best performance and safety levels, only level 4+ should operate along these road facilities or with dedicated lanes. The HD maps will also have very detailed information about the safe harbors – not only their presence but also their capacity and availability of free spaces.

A diamond-shaped chart is proposed to identify the smart level of the road as a function of LOSAD and ISAD (Figure 2). The shape of the diagram has been carefully developed, keeping ISAD and LOSAD separately and showing any improvement in the smart level of a road following a bottom-to-top path. While this chart presents all plausible combinations of LOSAD and ISAD, not all of them seem reasonable, i.e., cooperative driving support should never be provided to a road that cannot be driven by automated vehicles. These inadequate combinations have been cleared with a white pattern and identified with an asterisk.

This proposal establishes a framework that should be adapted to the specific circumstances of every country/region. These circumstances are related to the kind of parameters that could be retrieved from users/vehicles, national laws, enforcement level, characteristics of the road network (total length, type of infrastructure, etc.), existence of technology related to V2X communication, budgetary restrictions, among others. The bottom part of the chart presents two percentage scales for ISAD and LOSAD, corresponding with the cumulative percentage of the road network. This can be used by road administrations and operators to deduct the distribution of the smart levels as a function of the LOSAD/ISAD distribution. More detail about this procedure will be later provided.

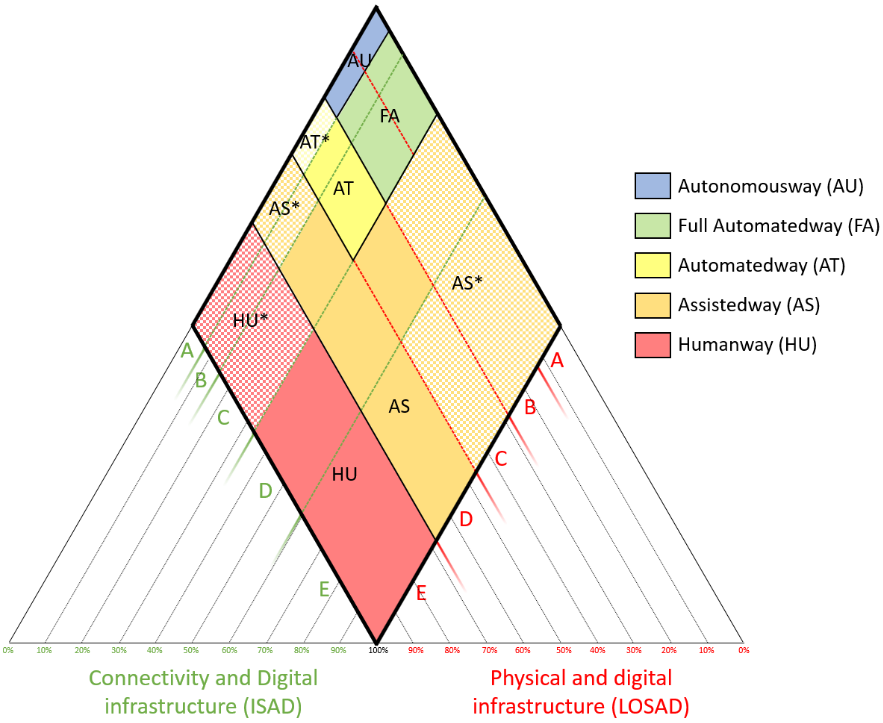


Figure 2. Diamond chart for the Smart Roads Classification.

In addition, the smart level can be used in line with the traditional classification system (i.e., in terms of mobility and accessibility), and with the classification systems involving users [1].

Although aggregated, every single zone of the LOSAD/ISAD combination might present some differences compared to the general description of the smart road level. These differences are minimum but can be seen in Figure 3.

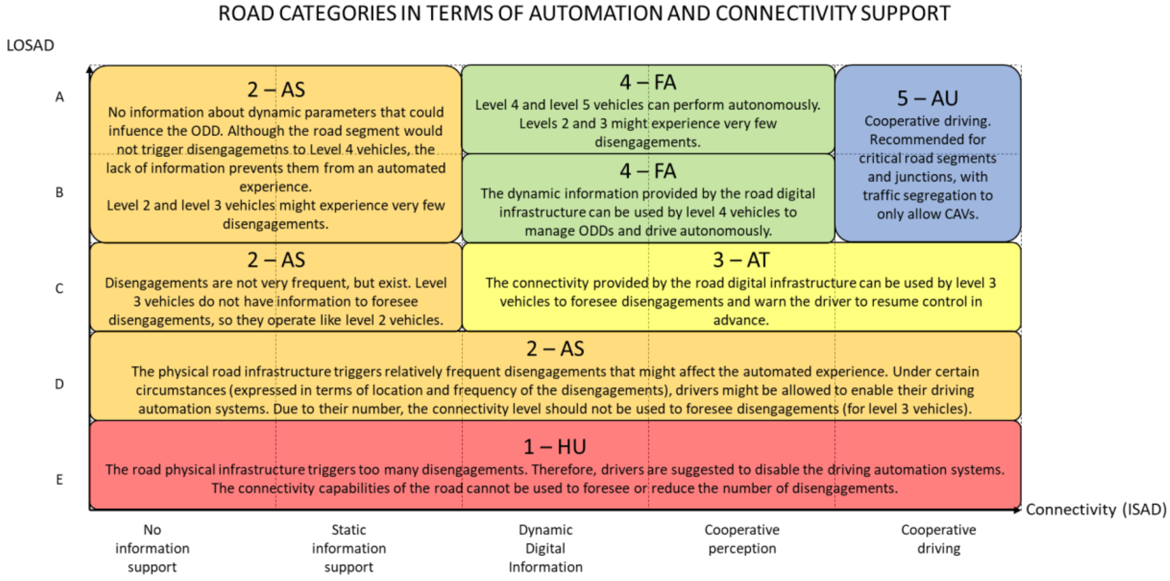


Figure 3. Description of the particularities of any ISAD/LOSAD combination. Minimum differences within the same SRC level can be seen.

Figure 4 represents the concept map of the SRC proposal, indicating the input factors from the different layers and the interaction with other classification systems. As it can be seen, ISAD and LOSAD can be used to determine the smart level, but the underlying factors can be used as well without prior determination of ISAD and LOSAD. In addition, the SRC is also connected to other existing classifications (road typology and the expanded classification including users). In fact, connectivity and/or automation create new kinds of user interactions. Traffic volume and composition are another group of factors that affect the infrastructure management.

Users should be able to perform along every type of road segment, except SRC level 5. This one uses the cooperative driving advantages, which require automation and connectivity. Therefore, these road segments should be restricted to very specific zones – or dedicated lanes – for which cooperative driving supposes a great improvement in terms of safety and/or performance. SRC level 4 road segments may not have any limitation regarding road users, but probably these road segments would apply to freeways and high-end two-lane rural roads. Therefore, road administrations and operators would be likely to prohibit certain users (e.g., pedestrians, bicycles, and LMV) as they do today.

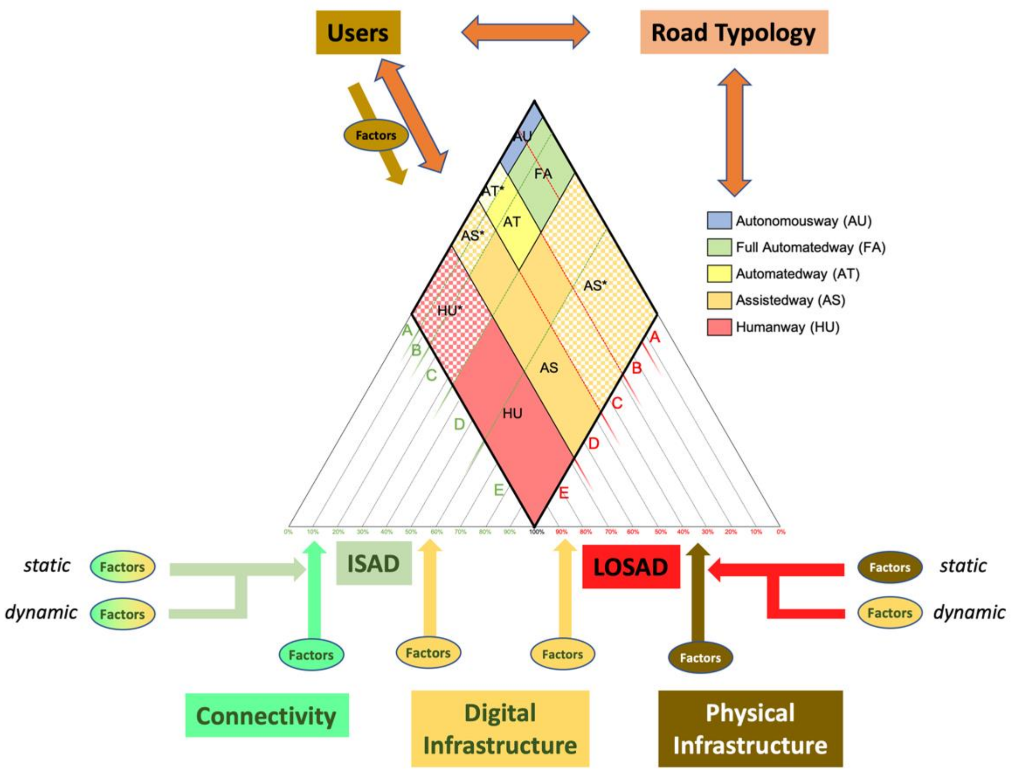


Figure 4. Smart Road Classification, including source data and interaction with other road classification systems.

Table 4 shows a detailed compilation of how the different users interact with every Smart Roads Classification level. The same color code applies for SRC levels.

C	A	Passenger car						Heavy vehicle						Motorcycle						Bicycle/LMV						Pedestrian					
✗	✗				1	2	X				1	2	X				1	2	X				1	2	X				1	2	X
✓	✗		3	3			X		3	3			X		3	3			X		3	3			X		3	3			X
✗	✓		3	4	4		X		3	4	4		X																		
✓	✓		3	3	4				3	3	4																				

C: connectivity. Does the user/vehicle present connectivity capabilities?

A: automation. Does the vehicle present automation capabilities?

The following codes describe the estimated limitations for the interaction between road segment and road user:

1: The road user cannot benefit from all advantages of the road.

2: The road user cannot benefit from all advantages of the road, but the road can detect it and inform other connected users.

3: The user presents connectivity and/or automation capabilities, but the smart level of the road is not able to provide/receive valuable information, and/or generates too many disengagements.

4: Same as 3, but adequacy depends on the SAE level of the vehicle and the LOSAD level of the road segment.

X: Non-connected and/or non-automated vehicles should not be allowed to perform at AU segments, since these would deprecate the performance of other CAVs.

Table 4. Interaction of the different users with the SRC levels.

It is worth to mention that the benefits for CAVs would also depend on the interaction between the SAE and the SRC level. Table 5 summarizes these interactions, highlighting where CAVs are more adequate, present no advantages, or are not permitted.

		SRC levels

		1. Humanway	2. Assistedway	3. Automated way	4. Full Automated way	5. Autonomous way
SAE levels	1					
	2 (with ACC+LKA)					
	3 without MRC					
	3 with MRC					
	4 (MRC included)					
	5 (MRC included)					

Note:	
	Adequate
	Allowed, but not especially benefited compared to lower SRC levels
	Prohibited
	Allowed, but many ODD may not be met and therefore human driving might prevail

Table 5. Particular interactions between the different SAE and SRC levels. SAE level 3 has been divided into two groups, depending on the availability of MRC capabilities.

The implementation of this system, however, should not wait explicit ODD definitions. Instead, road administrations and operators should define the SRC type for their road segments – or at least their best road segments – and let drivers decide whether they activate automation or not. It is important to remind that the ultimate responsibility of the driving task is the driver – either human or vehicle – and road administrations and operators should only provide the road segment characteristics for information purposes. Moreover, vehicles should not ever just rely on data transmitted from the infrastructure side. They should compare this information in a redundant way to what they perceive with their sensors.

3.2. Factors

The direct application of LOSAD and ISAD concepts can be used to determine the SRC of a road segment. As indicated at the introduction of section 3. SRC Framework, a more comprehensive table including specifications for every smart road level is provided. This table summarizes all LOSAD and ISAD factors and provides additional detail related to how ORSs should be materialized. While most ORS factors should be further researched, a few proposed values are given. In addition, the table distinguishes between the aspects that should be provided/ensured by road administrators and operators, and the requirements that every vehicle within the road segment should meet – if automation is activated –. It is important to highlight that the driver – either human or vehicle – is the ultimate responsible for the driving task. Road administrations and operators should make explicit the available automated driving supporting road characteristics for every Smart Road Level and the automated vehicle will decide whether it can switch on automated driving or not, according to the technologies it is equipped with.

Given the size of this table, it has been divided into five different ones, for the different smart road levels (see A2. Factors). In addition, all factors have been grouped into the following categories (these ones can also be found as the first column of the LOSAD and ISAD tables):

- **Physical infrastructure**. This layer includes the road typology, the geometric design of the road, pavement characteristics, road signage, and all other physical aspects related to the road and its environment. Moreover, different speed concepts as performance indicators are included (e.g., speed limit, operating speed, automated speed).

- **Digital infrastructure**. This category summarizes the availability of information for drivers and vehicles, as well as the physical facilities that the road presents to comply with that purpose. It includes aspects such as the presence and typology of Variable Message Signs, existence of maps and inventory, digital signing, and road/data sensors such as weather, safe harbors, and Roadside Units (RSUs).
- **Connectivity**. This group summarizes the connectivity capabilities of the road, including the V2X protocols and possibilities, 5G coverage, capacity of cooperative driving, etc.
- **Users**. This layer is not part of the LOSAD and ISAD tables but has been added to summarize the connectivity and automation implications for the potential users of the road facility.

3.3. Key Performance Indicators

Key Performance Indicators (KPIs) can be used by road administrations and operators to know the performance situation of their road network and make strategic decisions, maximizing the outcome of their investments. There are many possible actions that can be planned to increase road safety and traffic performance, affecting the highest number of people and having a clear picture of the starting situation. Many of these KPIs are alternate and require different sources of data. KPIs can also be used to compare the situation of a road network longitudinally (i.e., in time) and to the road networks of other countries or regions.

Three groups of KPIs are proposed:

- **Automation**. This KPI refers to the distribution of the disengagement rates per every smart road level, for the entire road network.
- **Safety**. This KPI focus on the average crash rate involving only CAVs of the road network.
- **Smart road level**. This final group of KPIs relate to the distribution of the LOSAD, ISAD, and SRC levels across the road network. It is especially interesting to see its current state and evolution in time. Comparisons between different regions of a road administration can be performed with them, as well.

Table 6 details the proposed KPIs for all groups. These primary KPIs could be used in calculations to obtain secondary KPIs that might be preferred by road administrations and operators.

	KPI
Automation	Disengagement rate per road segments of each smart road level, for the entire road network (disengagements/km or mi.)
Safety	Average Crash Rate involving CAVs for the entire road network
Smart road level	Percentage of each smart road level for the entire road network
	Percentage of each smart road level for every road type network
	Percentage of each ISAD level for the entire road network
	Percentage of each ISAD level for every road type network
	Percentage of each LOSAD level for the entire road network
	Percentage of each LOSAD level for every road type network

4. Appendices

1.1.1.30 A1. References

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1.1.1.31 A2. Factors

Humanway (HU)

This road segment type supposes no benefits to automation. Therefore, no requirements from the infrastructure side are proposed – just a few recommendations – (Table 7). These roads should be uploaded to digital, conventional maps (like nowadays). This level can be used by all road users regardless their transport mode, connectivity or automation capabilities (although other classification systems may limit specific road segments to some of them, such as freeways).

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type		
		Static	Road Segment	Dedicated lane	No	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)		
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)		
		Static	Road Segment	Lane width (m)		
		Static		Shoulder width (m)		
		Static	Road Section	Available stopping sight distance (m)		
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic		
		Static	Road Section	Minimum operating speed (km/h)		
		Static	Road Section	Automated speed (km/h)		
	Road markings	Static	Road Segment	Line width (mm)		
		Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity		

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
		Static	Road Section	Edge lines continuity (y/n)		
		Static	Road Section	Prevention of sun glaring		
	Signs	Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity		
		Static	Road Section	Contextual information		
		Static	Road segment	Readability of the VMS		
	Pavement	Static	Road Section	International Roughness Index (IRI) (m/km)		
		Static	Road Section	Longitudinal crack sealing		
		Static	Road Section	Hidden road markings		
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors		
	MRCs	Static	Road Segment	Availability of safe harbors		
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	Standard map (recommended)	
		Static	Road segment	Digital map update frequency	Manually	
		Static	Road segment	Road traffic and events ahead		
		Static	Road segment	Weather conditions		
		Static	Road section	Variable speed limit		
		Static	Road section	Traffic lights		
		Static	Road section	Traffic performance information		
		Static	Subject vehicle	Microscopic dynamic driving guidance		
		Static	Road Segment	Road works		
		Static	Road Segment	Presence of Roadside Units (RSUs)		

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
	Road equipment	Static	Road segment	Sensors for trajectories of vehicles and users		
		Static	Road segment	Automatic road data processing		
		Dynamic	Road Segment	Positioning accuracy		
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])		
	Weather	Static	Road Segment	Weather stations		
		Dynamic	Road Segment	Visibility (MOR)		
		Dynamic	Road Segment	Snow/icy pavement		
		Dynamic	Road section	Rainfall intensity		
	Sensing and information systems	Static	Road segment	Sensing system		
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system		
		Static	Road segment	Intelligent Speed Adaptation (ISA)		NA / Open
Connectivity	DSRC/ITS-G5	Static	Road section	Availability		
	C-V2X (5G)	Static	Road segment	Availability		
	DSRC	Dynamic	Road segment	Range (m)		
	Reliability	Dynamic	Road segment	% Packets received in due time		
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)		
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?		
	Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)		
Users		Static	Road segment	Presence of passenger cars	Y	

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
	User distribution	Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of LMV (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

Table 7. Factors for Humanway road segments.

Assisted way (AS)

This level includes some advantages, especially focused on lower SAE levels. Some Operational Road Sections (ORSs) may exist. Thus, some restrictions to geometry, environment, data usage, etc. are shown in addition to the basic LOSAD/ISAD factors.

As it can be seen in Table 8, some restrictions to road geometry apply. These restrictions would lead to a higher compatibility with vehicles' ODDs. Probably, the most remarkable restrictions are the minimum radius, minimum *K* for crest vertical curves, and cross-section. The proposed values are just examples and should be updated when ODDs become explicit and the effect of road infrastructure on vehicle disengagements are clearer. Digital maps may be similar than those for HU segments. Some additional information may be provided (e.g., from weather stations).

On the contrary to HU segments, these ones provide some support to automated vehicles. However, it should be stressed that not only should automated vehicles be able to perform along these segments – with more or less disengagements – but they should do it at a reasonable speed. In other words, an automated vehicle operating at 20 km/h would not be a reasonable solution.

This is why a restriction on how automated vehicles should operate must be provided. This does not mean that vehicles that do not meet these conditions are unable to perform along the road segment, but that they should not activate their autonomous systems.

The speed restrictions apply to vehicles – not to the road infrastructure – and are given in a range basis for every single road section. This means that a tangent would presumably require operating at a higher speed than a sharp horizontal curve. The parameter "Automated speed" refers to the minimum speed that an automated vehicle should be kept in automated mode, for a given section. As indicated in the literature review, it basically depends on road geometry and other environmental factors. Different criteria could be provided, most of them as a function of the speed limit for that road section:

- Automated speed should be equal or higher than the speed limit. Moreover, a specific Δv_a could be asked so $v_a \geq v_l + \Delta v_a$, where v_a is the automated speed and v_l is the speed limit.
- Similar to the previous constraint, the minimum automated speed could be asked in terms of a percentage of the speed limit, such as $v_a \geq \alpha_a \cdot v_l$, where $\alpha_a \geq 1$.
- A hard-coded value could be asked, too (e.g., $v_a \geq 100$ km/h), regardless the speed limit.

While not as important as the automated speed, a minimum value of the speed range could also be asked to vehicles. This is called “minimum operating speed”. This specification is important because nowadays some driving automation systems change their performance when performing slower than a certain speed. The threshold for this parameter could be indicated in a similar way than for the automated speed:

- Minimum operating speed equal or lower than a certain value, as a function of the speed limit: $v_m \leq v_l - \Delta v_m$, where v_m is the minimum operating speed and Δv_m is a positive speed differential.
- Similarly, another way of indicating the threshold could be: $v_m \leq \alpha_m \cdot v_l$, where $\alpha_m \leq 1$.
- Finally, hard-coded values could also apply.

It is important to mention that these limits are for free-flow conditions.

Layer	**Factor**	**Static/Dynamic**	**Domain**	**Parameter**	**2. Assistedway**	
					RA/RO	**Veh**
Physical infrastructure	Roadway type	Static	Road Segment	Type		
		Static	Road Segment	Dedicated lane	No	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>= 250	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=10	
		Static	Road Segment	Lane width (m)	2.8-4.0	

Layer	Factor	Static/Dynamic	Domain	Parameter	2. Assistedway	
		Static		Shoulder width (m)		
		Static	Road Section	Available stopping sight distance (m)		
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic		
		Static	Road Section	Minimum operating speed (km/h)		Different options
		Static	Road Section	Automated speed (km/h)		Different options
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity	150	
		Static	Road Section	Edge lines continuity (y/n)	Yes, except on entrance/exit ramps	
		Static	Road Section	Prevention of sun glaring		
	Signs	Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity		
		Static	Road Section	Contextual information		
		Static	Road segment	Readability of the VMS		
	Pavement	Static	Road Section	International Roughness Index (IRI) (m/km)		
		Static	Road Section	Longitudinal crack sealing		
		Static	Road Section	Hidden road markings		
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors		
	MRCs	Static	Road Segment	Availability of safe harbors		
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	Standard map	
		Static	Road segment	Digital map update frequency	Manually	
		Static	Road segment	Road traffic and events ahead		

Layer	Factor	Static/Dynamic	Domain	Parameter	2. Assistedway	
		Static	Road segment	Weather conditions		
		Static	Road section	Variable speed limit		
		Static	Road section	Traffic lights		
		Static	Road section	Traffic performance information		
		Static	Subject vehicle	Microscopic dynamic driving guidance		
		Static	Road Segment	Road works		
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)		
		Static	Road segment	Sensors for trajectories of vehicles and users		
		Static	Road segment	Automatic road data processing		
		Dynamic	Road Segment	Positioning accuracy	Accurate	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])		
	Weather	Static	Road Segment	Weather stations	Information from Weather Stations may be present.	
		Dynamic	Road Segment	Visibility (MOR)	200 m	
		Dynamic	Road Segment	Snow/icy pavement	Heavy snow	
		Dynamic	Road section	Rainfall intensity	Violent rain (<100 mm/h)	
	Sensing and information systems	Static	Road segment	Sensing system	N/Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system	N	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Open

Layer	Factor	Static/Dynamic	Domain	Parameter	2. Assistedway	
Connectivity	DSRC/ITS-G5	Static	Road section	Availability		
	C-V2X (5G)	Static	Road segment	Availability		
	DSRC	Dynamic	Road segment	Range (m)		
	Reliability	Dynamic	Road segment	% Packets received in due time		
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)		
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?		
	Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)		
Users	User distribution	Static	Road segment	Presence of passenger cars	Y	
		Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of LMV (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

Automated way (AT)

Automated way road segments suppose an important step in terms of automation. Connectivity becomes very relevant, and higher SAE levels could benefit of it, especially when retrieving data to determine the ODDs. Some examples are HD maps, information about the minimum available Stopping Sight Distance at a road section basis, information about the roadworks and other dynamic information that corresponds to the ISAD C level.

Road geometry and environment are also better to host automated vehicles. Some additional features may also help vehicles in their Dynamic Driving Task, such as light transition at tunnel exits or the presence of some safe harbors to find Minimal Risk Conditions.

Speed ranges should become wider than for AS segments (at least the upper threshold). All factors are summarized in Table 9.

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type		
		Static	Road segment	Dedicated lane	No	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>=300	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=15	
		Static	Road Segment	Lane width (m)	3.0-4.0	
		Static		Shoulder width (m)	>=2.5 m	
		Static	Road Section	Available stopping sight distance (m)	ASSD	
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic	Most static. Dynamic at critical locations	
		Static	Road Section	Minimum operating speed (km/h)		Different options
		Static	Road Section	Automated speed (km/h)		Different options
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity	150	
		Static	Road Section	Edge lines continuity (y/n)	Yes, including entrance/exit ramps	
		Static	Road Section	Prevention of sun glaring	Presence of dedicated lights at tunnel exits in order to mitigate sun glaring.	ADSs should have special features to adapt to low-contrast and sun-glared circumstances (e.g., W-E road orientations).
	Signs	Static	Road Segment	Contrast		

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
		Static	Road Segment	Retroreflectivity		
		Static	Road Section	Contextual information		Yes
		Static	Road segment	Readability of the VMS	Some restrictions apply	
	Pavement	Static	Road Section	International Roughness Index (IRI) (m/km)		
		Static	Road Section	Longitudinal crack sealing		
		Static	Road Section	Hidden road markings		
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors	If road works take place within an ORS, signage and geometry should meet ORS criteria	
	MRCs	Static	Road Segment	Availability of safe harbors	Some	
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	HD map	
		Static	Road segment	Digital map update frequency	Automatic, not necessarily real-time	
		Static	Road segment	Road traffic and events ahead	Y	
		Static	Road segment	Weather conditions	Y	
		Static	Road section	Variable speed limit	Variable Speed Limits are transmitted to vehicles	
		Static	Road section	Traffic lights	Y	
		Static	Road section	Traffic performance information	Macroscopic	
		Static	Subject vehicle	Microscopic dynamic driving guidance	Speed and lane advice might be sometimes provided	
		Static	Road Segment	Road works	Road works should be included in the HD maps.	
		Static	Road Segment	Presence of Roadside Units (RSUs)	RSUs are recommended, ensuring I2V	

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
	Road equipment	Static	Road segment	Sensors for trajectories of vehicles and users		
		Static	Road segment	Automatic road data processing	Y	
		Dynamic	Road Segment	Positioning accuracy	Very accurate	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])		
	Weather	Static	Road Segment	Weather stations	Information from WS is present [low representativity, hourly update]	
		Dynamic	Road Segment	Visibility (MOR)	500 m	
		Dynamic	Road Segment	Snow/icy pavement	Moderate snow	
		Dynamic	Road section	Rainfall intensity	Heavy rain (<50 mm/h)	
	Sensing and information systems	Static	Road segment	Sensing system	N/Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system	N/Y	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Closed
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Y/N	
	C-V2X (5G)	Static	Road segment	Availability	Y/N	
	DSRC	Dynamic	Road segment	Range (m)	2000	
	Reliability	Dynamic	Road segment	% Packets received in due time	99%	
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)	3	
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	100	

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
	Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	-85	
Users	User distribution	Static	Road segment	Presence of passenger cars	Y	
		Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of LMV (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

Full Automated way (FA)

Full Automated way road segments present similar connectivity conditions than Automated way road segments – in fact, they share the same ISAD levels –, but present better geometric and environmental conditions. This implies smoother radii and vertical curves, road markings, lane widths, etc. The most remarkable characteristic is that the whole section becomes an ORS, so all SAE level 4 vehicles should be able to operate driverless.

These road segments could be used at freeways and high-end two-lane rural roads. All users could operate along these road segments, but road administrations might be willing to limit the use to some users (e.g., not bicycles, LMV or pedestrians). This would probably be the case for the first road segments where automation would be fully encouraged. In addition, dedicated lanes could be used within a lower-level road. All factors are summarized in Table 10.

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type	Freeways and high-end two-lane rural roads	
		Static	Road segment	Dedicated lane	Optional	

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>=400	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=25	
		Static	Road Segment	Lane width (m)	3.25-3.8	
		Static		Shoulder width (m)	>=2.5 m	
		Static	Road Section	Available stopping sight distance (m)	ASSD	
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic	Dynamic	
		Static	Road Section	Minimum operating speed (km/h)		Different options
		Static	Road Section	Automated speed (km/h)		Different options
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity	150	
		Static	Road Section	Edge lines continuity (y/n)	Always	
		Static	Road Section	Prevention of sun glaring	Presence of dedicated lights at tunnel exits in order to mitigate sun glaring.	ADSs should have special features to adapt to low-contrast and sun-glared circumstances (e.g., W-E road orientations).
	Signs	Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity		
		Static	Road Section	Contextual information		Yes
		Static	Road segment	Readability of the VMS	High visibility/readability standards	

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
	Pavement	Static	Road Section	International Roughness Index (IRI) (m/km)	<=TBD	
		Static	Road Section	Longitudinal crack sealing	N	
		Static	Road Section	Hidden road markings	N	
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors	If road works take place within an ORS, signalization and geometry should meet ORS criteria	
	MRCs	Static	Road Segment	Availability of safe harbors	Yes [shoulders and medium-spaced harbours at junctions]	
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	HD map	
		Static	Road segment	Digital map update frequency	Automatic, not necessarily real-time	
		Static	Road segment	Road traffic and events ahead	Y	
		Static	Road segment	Weather conditions	Y	
		Static	Road section	Variable speed limit	Variable Speed Limits are transmitted to vehicles	
		Static	Road section	Traffic lights	Y	
		Static	Road section	Traffic performance information	Macroscopic	
		Static	Subject vehicle	Microscopic dynamic driving guidance	Speed and lane advice might be sometimes provided	
		Static	Road Segment	Road works	Road works should be included in the HD maps.	
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)	RSUs are recommended, ensuring I2V	
		Static	Road segment	Sensors for trajectories of vehicles and users		

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
		Static	Road segment	Automatic road data processing	Y	
		Dynamic	Road Segment	Positioning accuracy	Very accurate	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])	5 (TBD)	
	Weather	Static	Road Segment	Weather stations	Information from WS is present [high representativity, constantly updated]	
		Dynamic	Road Segment	Visibility (MOR)	1000 m	
		Dynamic	Road Segment	Snow/icy pavement	Light snow	
		Dynamic	Road section	Rainfall intensity	Moderate rain (<7.5 mm/h)	
	Sensing and information systems	Static	Road segment	Sensing system	Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system	N/Y	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Dynamic Closed
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Y/N	
	C-V2X (5G)	Static	Road segment	Availability	Y/N	
	DSRC	Dynamic	Road segment	Range (m)	2000	
	Reliability	Dynamic	Road segment	% Packets received in due time	99%	
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)	3	
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	100	
	Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	-85	

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
Users	User distribution	Static	Road segment	Presence of passenger cars	Y	
		Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of LMV (y/n)	N	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

Autonomous way (AU)

Finally, Autonomous way road segments represent the best option for automation. Like FA road segments, a single ORS appears throughout all their length. Additional facilities are also present, such as a high-density distribution of safe harbors which are also included in the HD maps. The most remarkable difference is that the connectivity support is remarkably better than for FA segments, enabling cooperative driving. Thus, these road segments are recommended for all zones with a high volume of vehicles, where dynamic traffic parameters could be used for managing purposes. Since non-connected vehicles cannot participate in the cooperative driving, these road segments would exclusive apply to freeways and only to connected and automated vehicles. These road segments should therefore be in exclusive road facilities, where needed and when the percentage of CAVs becomes important. To make their implementation cheaper, these could be placed as dedicated lanes in a lower-level road facility (SRC 4). Table 11 summarizes all factors.

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type	Freeways	
		Static	Road segment	Dedicated lane	Optional	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>=500	

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=30	
		Static	Road Segment	Lane width (m)	3.5-3.6	
		Static		Shoulder width (m)	>=2.5 m	
		Static	Road Section	Available stopping sight distance (m)	ASSD	
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic	Dynamic	
		Static	Road Section	Minimum operating speed (km/h)		Different options.
		Static	Road Section	Automated speed (km/h)		Different options.
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity	150	
		Static	Road Section	Edge lines continuity (y/n)	Always	
		Static	Road Section	Prevention of sun glaring	Presence of dedicated lights at tunnel exits in order to mitigate sun glaring.	ADSs should have special features to adapt to low-contrast and sun-glared circumstances (e.g., W-E road orientations).
	Signs	Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity		
		Static	Road Section	Contextual information		Yes
		Static	Road segment	Readability of the VMS	No restrictions (all vehicles and all information would be digital, too).	

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
	Pavement	Static	Road Section	International Roughness Index (IRI) (m/km)	<=TBD (comfort)	
		Static	Road Section	Longitudinal crack sealing	N	
		Static	Road Section	Hidden road markings	N	
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors	If road works take place within an ORS, signalization and geometry should meet ORS criteria	
	MRCs	Static	Road Segment	Availability of safe harbors	Yes [High frequency]	
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	HD map. MRC zones are included	
		Static	Road segment	Digital map update frequency	Real-time	
		Static	Road segment	Road traffic and events ahead	Y	
		Static	Road segment	Weather conditions	High precision data with forecasting possibilities	
		Static	Road section	Variable speed limit	Tailored Speed Advice is transmitted to vehicles	
		Static	Road section	Traffic lights	Y	
		Static	Road section	Traffic performance information	Microscopic, obtained by the road infrastructure	
		Static	Subject vehicle	Microscopic dynamic driving guidance	Y	
		Static	Road Segment	Road works	Road works should be included in the HD maps.	
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)	Yes, ensuring V2I and I2V	
		Static	Road segment	Sensors for trajectories of vehicles and users	Y	
		Static	Road segment	Automatic road data processing	Y	

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
		Dynamic	Road Segment	Positioning accuracy	Highest accuracy	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])	0 (TBD)	
	Weather	Static	Road Segment	Weather stations	Information from WS is present [high representativity, constantly updated]	
		Dynamic	Road Segment	Visibility (MOR)	1000 m	
		Dynamic	Road Segment	Snow/icy pavement	Light snow	
		Dynamic	Road section	Rainfall intensity	Moderate rain (<7.5 mm/h)	
	Sensing and information systems	Static	Road segment	Sensing system	Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)	Y	
		Static	Road segment	Information system	Y	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Dynamic Closed
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Y	
	C-V2X (5G)	Static	Road segment	Availability	Y	
	DSRC	Dynamic	Road segment	Range (m)	700	
	Reliability	Dynamic	Road segment	% Packets received in due time	100.00%	
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)	30	
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	5	
	Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	-67	
Users	User distribution	Static	Road segment	Presence of passenger cars	Yes, only CAVs	

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
		Static	Road segment	Presence of heavy vehicles (y/n)	Yes, only CAVs	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	N	
		Static	Road segment	Presence of bicycles (y/n)	N	
		Static	Road segment	Presence of LMV (y/n)	N	
		Static	Road segment	Presence of pedestrians (y/n)	N	

Table 11. Factors for Autonomous way road segments.

A2. LOSAD AND ISAD FACTORS

LOSAD, ISAD, and SRC factors are presented below, following the color code in **Erreur ! Source du renvoi introuvable.**. Green cells indicate a value proposal. Yellow cells indicate that the value should be defined by the road administrator or operator. Red cells indicate that a value should be provided when its effect on automation is better depicted. However, some values have been provided as a reference (TBD: to be determined).

	Proposed value
	To be researched specific thesholds based upon their effect on Automated Driving.
	To be defined by the Road Administration/Operator

Table 46 shows the static and dynamic factors that should be considered to decide the LOSAD level whereas Table 47 presents a compendium of all properties related to the digital infrastructure, and some requirements on the physical and connectivity parts. Some of the ISAD factors have been partially adapted from the originals indicated in the InfraMIX project, for clarification purposes. All factors are just suggested, given that these should be detailed by further research and international agreements about the standards.

Layer	Factor	Type	Domain	Parameter	Description	E	D	C	B	A
Physical Infrastructure	ORS	Static	Road Segment	Number	Number of ORS that should be within a road segment		<=5 (TBD)	<=2 (TBD)	1	1
			Road Segment	% of total length	Percentage of the total length of the road segment that should correspond to an ORS		75% (TBD)	90% (TBD)	100%	100%
Digital Infrastructure			Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])	Maximum allowable disengagement rate within ORSs, per time and length. All SAE levels are considered. Manual requests are not considered.				5 (TBD)	0 (TBD)
	Weather and Lighting conditions	Dynamic	Road Segment	Visibility (MOR)	Visibility range from weather stations		200 m	500 m	1000 m	1000 m
		Dynamic	Road Segment	Snow/icy pavement	Ice on the pavement may reduce the skid resistance and therefore prevent adequate automation. Snow on the pavement may prevent to distinguish road markings.		Heavy snow	Moderate snow	Light snow	Light snow
		Dynamic	Road section	Rainfall intensity	Rainfall may limit visibility.		Violent rain (<100 mm/h)	Heavy rain (<50 mm/h)	Moderate rain (<7.5 mm/h)	Light rain (<2.5 mm/h)
		Static	Road Segment	Lighting	Availability					

Table 46. Factors related to LOSAD.

Layer	Factor		Domain	Parameter	Description	E	D	C	B	A
Digital Infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	Availability of a digital map with static road signs, junctions, etc.		Standard map	HD map	HD map. MRC zones are included	HD map. MRC zones are included
		Static	Road segment	Digital map update frequency	How frequent are maps updated?		Manually	Automatic, not necessarily real-time	Real-time	Real-time
		Static	Road segment	Road traffic and events ahead	Availability of DIGITAL information related to road traffic and events ahead (Incident and hazard warnings)			Y	Y	Y
		Static	Road segment	Weather conditions	Availability of DIGITAL information related to weather conditions			Y	High precission data with forecasting possibilities	High precission data with forecasting possibilities
		Static	Road section	Variable speed limit	Availability of DIGITAL information related to Variable Speed Limit			Variable Speed Limits are transmitted to vehicles	Variable Speed Limits are transmitted to vehicles	Tailored Speed Advice is transmitted to vehicles
		Static	Road section	Traffic lights	Availability of DIGITAL information related to traffic lights			Y	Y	Y
		Static	Road section	Traffic performance information	Availability of traffic data for management, indications, and other purposes			Macroscopic	Microscopic, obtained from vehicle data	Microscopic, obtained by the road infrastructure
		Static	Subject vehicle	Microscopic dynamic driving guidance	Can the Digital Infrastructure provide tailored instructions in a vehicle-basis? (i.e., cooperative driving)				Speed and lane advice might be sometimes provided	Y

Layer	Factor		Domain	Parameter	Description	E	D	C	B	A
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)	Are there RSUs?				Yes, ensuring I2V	Yes, ensuring V2I and I2V
		Static	Road segment	Sensors for trajectories of vehicles and users	Specific road sensors to detect the presence and trajectories of vehicles/users				Y/N	Y
		Static	Road segment	Automatic road data processing	Can the infrastructure automatically process information from multiple sensors (e.g., in-pavement sensors, cameras, ramp metering...)			Y	Y	Y
		Dynamic	Road Segment	Positioning accuracy	How accurate is the position of vehicles, despite the specific equipment used (RTK land stations or reference points)		Accurate	Very accurate	Highest accuracy	Highest accuracy
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Short range communication			Y/N	Y	Y
	C-V2X (5G)	Static	Road segment	Availability	Cellular V2X (Vehicle-to-Everything) communication			Y/N	Y	Y
	DSRC/ITS-G5	Dynamic	Road segment	Range (m)	This range is related to RSUs density			2000	1700	700
	Reliability	Dynamic	Road segment	% Packets received in due time	This is related to signal strength fluctuations			99%	99.90%	100.00%
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)				3	6	30
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	This is a measure of delay			100	40	5

Layer	Factor		Domain	Parameter	Description	E	D	C	B	A
	C-V2X Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	The average power received from a single Reference signal			-85	-82	-67

Table 47. Factors related to ISAD.

A3. SRC FACTORS

A3.1 Humanway (HU)

This road segment type supposes no benefits to automation. Therefore, no requirements from the infrastructure side are proposed – just a few recommendations – (Table 48). These roads should be uploaded to digital, conventional maps (like nowadays). This level can be used by all road users regardless their transport mode, connectivity or automation capabilities (although other classification systems may limit specific road segments to some of them, such as freeways).

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type		
		Static	Road Segment	Dedicated lane	No	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)		
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)		
		Static	Road Segment	Lane width (m)		
		Static		Shoulder width (m)		
		Static	Road Section	Available stopping sight distance (m)		
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic		
		Static	Road Section	Minimum operating speed (km/h)		
		Static	Road Section	Automated speed (km/h)		
	Road markings	Static	Road Segment	Line width (mm)		
		Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity (cd/lx/m^2)		
		Static	Road Section	Edge lines continuity (y/n)		
		Static	Road Section	Prevention of sun glaring		
	Signs	Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity (cd/lx/m^2)		
		Static	Road Section	Contextual information		
		Static	Road segment	Readability of the VMS		

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
	Pavement	Static	Road Section	Roughness (IRI)		
		Static	Road Section	Longitudinal crack sealing		
		Static	Road Section	Hidden road markings		
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors		
	MRCs	Static	Road Segment	Availability of safe harbors		
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	Standard map (recommended)	
		Static	Road segment	Digital map update frequency	Manually	
		Static	Road segment	Road traffic and events ahead		
		Static	Road segment	Weather conditions		
		Static	Road section	Variable speed limit		
		Static	Road section	Traffic lights		
		Static	Road section	Traffic performance information		
		Static	Subject vehicle	Microscopic dynamic driving guidance		
		Static	Road Segment	Road works		
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)		
		Static	Road segment	Sensors for trajectories of vehicles and users		
		Static	Road segment	Automatic road data processing		
		Dynamic	Road Segment	Positioning accuracy		
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])		
		Static	Road Segment	Weather stations		

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
	Weather and Lighting conditions	Dynamic	Road Segment	Visibility (MOR)		
		Dynamic	Road Segment	Snow/icy pavement		
		Dynamic	Road section	Rainfall intensity		
		Static	Road Segment	Availability of Lighting		
	Sensing and information systems	Static	Road segment	Sensing system		
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system		
		Static	Road segment	Intelligent Speed Adaptation (ISA)		NA / Open
Connectivity	DSRC/ITS-G5	Static	Road section	Availability		
	C-V2X (5G)	Static	Road segment	Availability		
	DSRC/ITS-G5	Dynamic	Road segment	Range (m)		
	Reliability	Dynamic	Road segment	% Packets received in due time		
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)		
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?		
	C-V2X Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)		
Users	User distribution	Static	Road segment	Presence of passenger cars	Y	
		Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	

Layer	Factor	Static/Dynamic	Domain	Parameter	1. Humanway	
		Static	Road segment	Presence of LMV (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

Table 48. Factors for Humanway road segments.

A3.2 Assisted way (AS)

This level includes some advantages, especially focused on lower SAE levels. Some Operational Road Sections (ORSs) may exist. Thus, some restrictions to geometry, environment, data usage, etc. are shown in addition to the basic LOSAD/ISAD factors.

As it can be seen in **Erreur ! Source du renvoi introuvable.**, some restrictions to road geometry apply. T hese restrictions would lead to a higher compatibility with vehicles' ODDs. Probably, the most remarkable restrictions are the minimum radius, minimum K for crest vertical curves, and cross-section. The proposed values are just examples, and should be updated when ODDs become explicit and the effect of road infrastructure on vehicle disengagements are more clear. New restrictions apply for automated vehicles regarding speed, which will be explain after the table.

Digital maps may be similar than those for HU segments. Some additional information may be provided (e.g., from weather stations).

Layer	Factor	Static/Dynamic	Domain	Parameter	2. Assistedway	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type		
		Static	Road Segment	Dedicated lane	No	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>= 250	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=10	
		Static	Road Segment	Lane width (m)	2.8-4.0	
		Static		Shoulder width (m)		
		Static	Road Section	Available stopping sight distance (m)		
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic		
		Static	Road Section	Minimum operating speed (km/h)		Different options
		Static	Road Section	Automated speed (km/h)		Different options
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity (cd/lx/m^2)	150	
		Static	Road Section	Edge lines continuity (y/n)	Yes, except on entrance/exit ramps	
		Static	Road Section	Prevention of sun glaring		
	Signs	Static	Road Segment	Contrast		
		Static	Road Segment	Retroreflectivity (cd/lx/m^2)		
		Static	Road Section	Contextual information		
		Static	Road segment	Readability of the VMS		

Layer	Factor	Static/Dynamic	Domain	Parameter	2. Assistedway	
	Pavement	Static	Road Section	Roughness (IRI)		
		Static	Road Section	Longitudinal crack sealing		
		Static	Road Section	Hidden road markings		
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors		
	MRCs	Static	Road Segment	Availability of safe harbors		
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	Standard map	
		Static	Road segment	Digital map update frequency	Manually	
		Static	Road segment	Road traffic and events ahead		
		Static	Road segment	Weather conditions		
		Static	Road section	Variable speed limit		
		Static	Road section	Traffic lights		
		Static	Road section	Traffic performance information		
		Static	Subject vehicle	Microscopic dynamic driving guidance		
		Static	Road Segment	Road works		
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)		
		Static	Road segment	Sensors for trajectories of vehicles and users		
		Static	Road segment	Automatic road data processing		
		Dynamic	Road Segment	Positioning accuracy	Accurate	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])		
	Weather and Lighting conditions	Static	Road Segment	Weather stations	Information from Weather Stations may be present.	

Layer	Factor	Static/Dynamic	Domain	Parameter	2. Assistedway	
		Dynamic	Road Segment	Visibility (MOR)	200 m	
		Dynamic	Road Segment	Snow/icy pavement	Heavy snow	
		Dynamic	Road section	Rainfall intensity	Violent rain (<100 mm/h)	
		Static	Road Segment	Availability of Lighting		
	Sensing and information systems	Static	Road segment	Sensing system	N/Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system	N	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Open
Connectivity	DSRC/ITS-G5	Static	Road section	Availability		
	C-V2X (5G)	Static	Road segment	Availability		
	DSRC/ITS-G5	Dynamic	Road segment	Range (m)		
	Reliability	Dynamic	Road segment	% Packets received in due time		
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)		
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?		
	C-V2X Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)		
Users	User distribution	Static	Road segment	Presence of passenger cars	Y	
		Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	

Layer	Factor	Static/Dynamic	Domain	Parameter	2. Assistedway	
		Static	Road segment	Presence of LMV (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

On the contrary to HU segments, these ones provide some support to automated vehicles. However, it should be stressed that not only should automated vehicles be able to perform along these segments – with more or less disengagements – but they should do it at a reasonable speed. In other words, an automated vehicle operating at 20 km/h would not be a reasonable solution.

This is why a restriction on how automated vehicles should operate must be provided. This does not mean that vehicles that do not meet these conditions are unable to perform along the road segment, but that they should not activate their autonomous systems.

The speed restrictions apply to vehicles – not to the road infrastructure – and are given in a range basis for every single road section. This means that a tangent would presumably require operating at a higher speed than a sharp horizontal curve. The parameter "Automated speed" refers to the minimum speed that an automated vehicle should be kept in automated mode, for a given section. As indicated in the literature review, it basically depends on road geometry and other environmental factors. Different criteria could be provided, most of them as a function of the speed limit for that road section:

- Automated speed should be equal or higher than the speed limit. Moreover, an specific Δv_a could be asked so $v_a \geq v_l + \Delta v_a$, where v_a is the automated speed and v_l is the speed limit.
- Similarly to the previous constraint, the minimum automated speed could be asked in terms of a percentage of the speed limit, such as $v_a \geq \alpha_a \cdot v_l$, where $\alpha_a \geq 1$.
- A hard-coded value could be asked, too (e.g., $v_a \geq 100$ km/h), regardless the speed limit.

While not as important as the automated speed, a minimum value of the speed range could also be asked to vehicles. This is called "minimum operating speed". This specification is important because nowadays, some driving automation systems change their performance when performing slower than a certain speed. The threshold for this parameter could be indicated in a similar way than for the automated speed:

- Minimum operating speed equal or lower than a certain value, as a function of the speed limit: $v_m \leq v_l - \Delta v_m$, where v_m is the minimum operating speed and Δv_m is a positive speed differential.
- Similarly, another way of indicating the threshold could be: $v_m \leq \alpha_m \cdot v_l$, where $\alpha_m \leq 1$.
- Finally, hard-coded values could also apply.

It is important to mention that these limits are for free-flow conditions.

A3.3 Automated way (AT)

Automated way road segments suppose an important step in terms of automation. Connectivity becomes very relevant, and higher SAE levels could benefit of it, especially when retrieving data to determine the ODDs. Some examples are HD maps, information about the minimum available Stopping Sight Distance at a road section basis, information about the roadworks and other dynamic information that corresponds to the ISAD C level.

Road geometry and environment are also better to host automated vehicles. Some additional features may also help vehicles in their Dynamic Driving Task, such as light transition at tunnel exits or the presence of some safe harbors to help find Minimal Risk Conditions.

Speed ranges should become wider than for AS segments (at least the upper threshold). All factors are summarized in Table 49.

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type		
		Static	Road segment	Dedicated lane	No	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>=300	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=15	
		Static	Road Segment	Lane width (m)	3.0-4.0	
		Static		Shoulder width (m)	>=2.5 m	
		Static	Road Section	Available stopping sight distance (m)	ASSD	
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic	Most static. Dynamic at critical locations	
		Static	Road Section	Minimum operating speed (km/h)		Different options
		Static	Road Section	Automated speed (km/h)		Different options
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity (cd/lx/m^2)	150	
		Static	Road Section	Edge lines continuity (y/n)	Yes, including entrance/exit ramps	
		Static	Road Section	Prevention of sun glaring	Presence of dedicated lights at tunnel exits in order to mitigate sun glaring.	ADSs should have special features to adapt to low-contrast and sun-glared circumstances (e.g., W-E road orientations).
	Signs	Static	Road Segment	Contrast		

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
		Static	Road Segment	Retroreflectivity (cd/lx/m²)		
		Static	Road Section	Contextual information		Yes
		Static	Road segment	Readability of the VMS	Some restrictions apply	
	Pavement	Static	Road Section	Roughness (IRI)		
		Static	Road Section	Longitudinal crack sealing		
		Static	Road Section	Hidden road markings		
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors	If road works take place within an ORS, signage and geometry should meet ORS criteria	
	MRCs	Static	Road Segment	Availability of safe harbors	Some	
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	HD map	
		Static	Road segment	Digital map update frequency	Automatic, not necessarily real-time	
		Static	Road segment	Road traffic and events ahead	Y	
		Static	Road segment	Weather conditions	Y	
		Static	Road section	Variable speed limit	Variable Speed Limits are transmitted to vehicles	
		Static	Road section	Traffic lights	Y	
		Static	Road section	Traffic performance information	Macroscopic	
		Static	Subject vehicle	Microscopic dynamic driving guidance	Speed and lane advice might be sometimes provided	
		Static	Road Segment	Road works	Road works should be included in the HD maps.	
		Static	Road Segment	Presence of Roadside Units (RSUs)	RSUs are recommended, ensuring I2V	

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
	Road equipment	Static	Road segment	Sensors for trajectories of vehicles and users		
		Static	Road segment	Automatic road data processing	Y	
		Dynamic	Road Segment	Positioning accuracy	Very accurate	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])		
	Weather and Lighting conditions	Static	Road Segment	Weather stations	Information from WS is present [low representativity, hourly update]	
		Dynamic	Road Segment	Visibility (MOR)	500 m	
		Dynamic	Road Segment	Snow/icy pavement	Moderate snow	
		Dynamic	Road section	Rainfall intensity	Heavy rain (<50 mm/h)	
		Static	Road Segment	Availability of Lighting		
	Sensing and information systems	Static	Road segment	Sensing system	N/Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system	N/Y	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Closed
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Y/N	
	C-V2X (5G)	Static	Road segment	Availability	Y/N	
	DSRC/ITS-G5	Dynamic	Road segment	Range (m)	2000	
	Reliability	Dynamic	Road segment	% Packets received in due time	99%	
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)	3	

Layer	Factor	Static/Dynamic	Domain	Parameter	3. Automated way	
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	100	
	C-V2X Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	-85	
Users	User distribution	Static	Road segment	Presence of passenger cars	Y	
		Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of LMV (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

Table 49. Factors for Automated way road segments.

A3.4 Full Automated way (FA)

Full Automated way road segments present similar connectivity conditions than Automated way road segments (in fact, they share the same ISAD levels), but present better geometric and environmental conditions. This implies smoother radii and vertical curves, road markings, lane widths, etc. The most remarkable characteristic is that the whole section becomes an ORS, so all SAE level 4 vehicles should be able to operate driverless.

These road segments could be used at freeways and high-end two-lane rural roads. All users could operate along these road segments, but authorities might be willing to limit the use to some users (e.g., not bicycles, LMV or pedestrians). This would probably be the case for the first road segments where automation would be fully encouraged. In addition, dedicated lanes could be used within a lower-level road. All factors are summarized in Table 39.

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type	Freeways and high-end two-lane rural roads	
		Static	Road segment	Dedicated lane	Optional	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>=400	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=25	
		Static	Road Segment	Lane width (m)	3.25-3.8	
		Static		Shoulder width (m)	>=2.5 m	
		Static	Road Section	Available stopping sight distance (m)	ASSD	
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic	Dynamic	
		Static	Road Section	Minimum operating speed (km/h)		Different options
		Static	Road Section	Automated speed (km/h)		Different options
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity (cd/lx/m²)	150	
		Static	Road Section	Edge lines continuity (y/n)	Always	
		Static	Road Section	Prevention of sun glaring	Presence of dedicated lights at tunnel exits in order to mitigate sun glaring.	ADSs should have special features to adapt to low-contrast and sun-glared circumstances (e.g., W-E road orientations).
	Signs	Static	Road Segment	Contrast		

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
		Static	Road Segment	Retroreflectivity (cd/lx/m²)		
		Static	Road Section	Contextual information		Yes
		Static	Road segment	Readability of the VMS	High visibility/readability standards	
	Pavement	Static	Road Section	Roughness (IRI)	<=TBD	
		Static	Road Section	Longitudinal crack sealing	N	
		Static	Road Section	Hidden road markings	N	
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors	If road works take place within an ORS, signalization and geometry should meet ORS criteria	
	MRCs	Static	Road Segment	Availability of safe harbors	Yes [shoulders and medium-spaced harbours at junctions]	
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	HD map	
		Static	Road segment	Digital map update frequency	Automatic, not necessarily real-time	
		Static	Road segment	Road traffic and events ahead	Y	
		Static	Road segment	Weather conditions	Y	
		Static	Road section	Variable speed limit	Variable Speed Limits are transmitted to vehicles	
		Static	Road section	Traffic lights	Y	
		Static	Road section	Traffic performance information	Macroscopic	
		Static	Subject vehicle	Microscopic dynamic driving guidance	Speed and lane advice might be sometimes provided	
		Static	Road Segment	Road works	Road works should be included in the HD maps.	
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)	RSUs are recommended, ensuring I2V	

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
		Static	Road segment	Sensors for trajectories of vehicles and users		
		Static	Road segment	Automatic road data processing	Y	
		Dynamic	Road Segment	Positioning accuracy	Very accurate	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])	5 (TBD)	
	Weather and Lighting conditions	Static	Road Segment	Weather stations	Information from WS is present [high representativity, constantly updated]	
		Dynamic	Road Segment	Visibility (MOR)	1000 m	
		Dynamic	Road Segment	Snow/icy pavement	Light snow	
		Dynamic	Road section	Rainfall intensity	Moderate rain (<7.5 mm/h)	
		Static	Road Segment	Availability of Lighting		
	Sensing and information systems	Static	Road segment	Sensing system	Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)		
		Static	Road segment	Information system	N/Y	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Dynamic Closed
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Y/N	
	C-V2X (5G)	Static	Road segment	Availability	Y/N	
	DSRC/ITS-G5	Dynamic	Road segment	Range (m)	2000	
	Reliability	Dynamic	Road segment	% Packets received in due time	99%	
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)	3	

Layer	Factor	Static/Dynamic	Domain	Parameter	4. Full Automated way	
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	100	
	C-V2X Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	-85	
Users	User distribution	Static	Road segment	Presence of passenger cars	Y	
		Static	Road segment	Presence of heavy vehicles (y/n)	Y	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	Y	
		Static	Road segment	Presence of bicycles (y/n)	Possible, depending on other classifications	
		Static	Road segment	Presence of LMV (y/n)	N	
		Static	Road segment	Presence of pedestrians (y/n)	Possible, depending on other classifications	

A3.5 Autonomous way (AU)

Finally, Autonomous way road segments represent the best option for automation. Like FA road segments, a single ORS appears throughout all their length. Additional facilities are also present, such as a high-density distribution of safe harbors which are also included in the HDmaps. The most remarkable difference is that the connectivity support is remarkably better than for FA segments, enabling cooperative driving. Thus, these road segments are recommended for all zones with a high volume of vehicles, where dynamic traffic parameters could be used for managing purposes. Since non-connected vehicles cannot participate in the cooperative driving, these road segments would exclusive apply to freeways and only to connected and automated vehicles. These road segments should therefore be in exclusive road facilities, where needed and when the percentage of CAVs becomes important. To make their implementation cheaper, these could be placed as dedicated lanes in a lower-level road facility (SRC 4). Table 50 summarizes all factors.

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
					RA/RO	Veh
Physical infrastructure	Roadway type	Static	Road Segment	Type	Freeways	
		Static	Road segment	Dedicated lane	Optional	
	Geometric design	Static	Road Segment - Horizontal curves	Minimum Radius (m)	>=500	
		Static	Road Segment - Crest vertical curves	Minimum K (m/%)	>=30	
		Static	Road Segment	Lane width (m)	3.5-3.6	
		Static		Shoulder width (m)	>=2.5 m	
		Static	Road Section	Available stopping sight distance (m)	ASSD	
	Speed	Static	Road Segment/Section	Speed limit (km/h): Static; Dynamic	Dynamic	
		Static	Road Section	Minimum operating speed (km/h)		Different options.
		Static	Road Section	Automated speed (km/h)		Different options.
	Road markings	Static	Road Segment	Line width (mm)	150	
		Static	Road Segment	Contrast	3	
		Static	Road Segment	Retroreflectivity (cd/lx/m²)	150	
		Static	Road Section	Edge lines continuity (y/n)	Always	
		Static	Road Section	Prevention of sun glaring	Presence of dedicated lights at tunnel exits in order to mitigate sun glaring.	ADSs should have special features to adapt to low-contrast and sun-glared circumstances (e.g., W-E road orientations).
	Signs	Static	Road Segment	Contrast		

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
		Static	Road Segment	Retroreflectivity (cd/lx/m²)		
		Static	Road Section	Contextual information		Yes
		Static	Road segment	Readability of the VMS	No restrictions (all vehicles and all information would be digital, too).	
	Pavement	Static	Road Section	Roughness (IRI)	<=TBD (comfort)	
		Static	Road Section	Longitudinal crack sealing	N	
		Static	Road Section	Hidden road markings	N	
	Road works	Static	Road Segment	Compliance of geometry, markings, signs and pavement factors	If road works take place within an ORS, signalization and geometry should meet ORS criteria	
	MRCs	Static	Road Segment	Availability of safe harbors	Yes [High frequency]	
Digital infrastructure	Mapping and digital information availability	Static	Road segment	Digital map	HD map. MRC zones are included	
		Static	Road segment	Digital map update frequency	Real-time	
		Static	Road segment	Road traffic and events ahead	Y	
		Static	Road segment	Weather conditions	High precission data with forecasting possibilities	
		Static	Road section	Variable speed limit	Tailored Speed Advice is transmitted to vehicles	
		Static	Road section	Traffic lights	Y	
		Static	Road section	Traffic performance information	Microscopic, obtained by the road infrastructure	
		Static	Subject vehicle	Microscopic dynamic driving guidance	Y	
		Static	Road Segment	Road works	Road works should be included in the HD maps.	
	Road equipment	Static	Road Segment	Presence of Roadside Units (RSUs)	Yes, ensuring V2I and I2V	

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
		Static	Road segment	Sensors for trajectories of vehicles and users	Y	
		Static	Road segment	Automatic road data processing	Y	
		Dynamic	Road Segment	Positioning accuracy	Highest accuracy	
	Disengagements	Dynamic	Road Section	Maximum disengagement density and frequency rate (d/[km*h*V_AV])	0 (TBD)	
	Weather and Lighting conditions	Static	Road Segment	Weather stations	Information from WS is present [high representativity, constantly updated]	
		Dynamic	Road Segment	Visibility (MOR)	1000 m	
		Dynamic	Road Segment	Snow/icy pavement	Light snow	
		Dynamic	Road section	Rainfall intensity	Moderate rain (<7.5 mm/h)	
		Static	Road Segment	Availability of Lighting		
	Sensing and information systems	Static	Road segment	Sensing system	Y	
		Static	Road segment	Availability of Stationary Object Detection system (radar-based side units)	Y	
		Static	Road segment	Information system	Y	
		Static	Road segment	Intelligent Speed Adaptation (ISA)		Dynamic Closed
Connectivity	DSRC/ITS-G5	Static	Road section	Availability	Y	
	C-V2X (5G)	Static	Road segment	Availability	Y	
	DSRC/ITS-G5	Dynamic	Road segment	Range (m)	700	
	Reliability	Dynamic	Road segment	% Packets received in due time	100.00%	
	AV Throughput	Dynamic	Road segment	Average data rate (Mbps)	30	

Layer	Factor	Static/Dynamic	Domain	Parameter	5. Autonomous way	
	Latency	Dynamic	Road segment	Time required to reach destination (ms)?	5	
	C-V2X Signal strength	Dynamic	Road segment	Reference Signal Received Power (RSRP) (dBm)	-67	
Users	User distribution	Static	Road segment	Presence of passenger cars	Yes, only CAVs	
		Static	Road segment	Presence of heavy vehicles (y/n)	Yes, only CAVs	
		Static	Road segment	Presence of motorcycles (mopeds included) (y/n)	N	
		Static	Road segment	Presence of bicycles (y/n)	N	
		Static	Road segment	Presence of LMV (y/n)	N	
		Static	Road segment	Presence of pedestrians (y/n)	N	

Table 50. Factors for Autonomous way road segments.

A4. QUESTIONNAIRES

A4.1 Questionnaire 1

International Survey for PIARC Special Project

“Smart Roads Classification”

Questionnaire 1
National/Regional Road Administrations and Road Operators

*Grey-shaded information will be gathered by the UPV Team, so it will not be included in the questionnaire to be sent to road administrations. Additionally, the source considered for collecting the information is attached. The text by default (to be overridden by the respondents) is provided in grey, italic font).

This questionnaire is part of the PIARC Special Project “Smart Roads Classification” that aims at exploring a new framework for the classification of the road infrastructure based on its physical characteristics as well as on its reception capacity of the automation and connectivity of the vehicles.

Given that the presence of Connected and Automated Vehicles (CAVs) is on the increase, it is necessary to explore a new Smart Roads Classification (SRC) system that provides information to users and vehicles on their degree of adaptation to automated and/or connected driving. This information should range from indicating which road sections do not allow any type of autonomous driving, to sections that are ready for any autonomous system, going through various intermediate degrees depending on the technology.

In order to achieve a simple-to-use and rapid-to-implement tool, it is important to identify the current methods and procedures for road classification, and the main concerns of road administrations. Thus, the objective of this questionnaire is to collect general information about the current road network characteristics and the priorities of road-related agencies and road operators.

The time required to complete this questionnaire is estimated to average 30-45 minutes per response, without including existing data search.

Do you represent a road administration or a road operator?	***[Closed-ended question]***

General questions	
Agency or Administration // Operator	*[Open-ended question]*
Country	*[Open-ended question]*

Continent/Region	*[Nominal question: Africa, Asia, Australasia, Europe, North America, South America]*
Please, could you identify a person within your institution who we could contact for any additional information?	
Contact person	*[Open-ended question]*
Position	*[Open-ended question]*
Email	*[Open-ended question]*

Economic indicators	
Gross Domestic Product (GDP)	World Bank
Gross Domestic Product (GDP) growth	World Bank
Gross Domestic Product (GDP) per capita	World Bank
Structure of the economy (% of GDP)	
Agriculture, forestry, and fishing	World Bank
Industry, including construction	World Bank
Services	World Bank
Population	
Total	World Bank
Urban population	World Bank
Total primary energy supply by source	International Energy Agency
Total road spending	OECD
Road maintenance expenditure	OECD
Road Safety Level (deaths per 100k people)	WHO

Characterization of the national/regional road network
Current Road classification system

Indicate which road categories are used in your current road classification system for each of the following areas (if applicable)

[Open-ended question]

Functionality	Ownership	Morphology	Environment	Orography	Users	Pavement	Others
• ***Freeway*** • ***Arterial*** • ***Collector*** • ***Local***	• *National* • *State* • *Regional* • *Provincial* • *Local*	• *Freeway* • *Multilane* • *Two-lane rural*	• *Rural* • *Suburban* • *Urban*	• *Flat* • *Terrain* • *Mountainous*	• *Motorized* • *Non-motorized* • *Mix*	• *Paved* • *Unpaved*	

Road density (km/km²)	OECD, Globio, CIA
Road quality	World Economic Forum
Network length per road category	
Freeway/Expressway/Multilane	OECD, UNECE, Wikipedia
Two-lane rural roads	OECD
Unpaved roads (%)	CIA

Type of road users per road category (real users, not only allowed users)

Examples of road users

- *High speed motorized vehicles (heavy vehicles and cars)*
- *Low speed motorized vehicles (motorcycles, mopeds, and others)*
- *Non-motorized vehicles (bicycles, electric assisted bicycles, and tricycles)*
- *Pedestrians*

Freeway/Expressway	*[Closed-ended question] [Matrix]*
Multilane highway	
Two-lane rural road	
Crosstown road	
Unpaved rural road	

Traffic volume

Indicate the usual minimum and maximum Annual Average Daily Traffic (AADT) per road category, in vehicles per day

	Minimum AADT	Maximum AADT
Freeway/Expressway	*[Open-ended question]*	*[Open-ended question]*
Multilane highway	*[Open-ended question]*	*[Open-ended question]*
Two-lane rural road	*[Open-ended question]*	*[Open-ended question]*

Speed limit

Indicate the maximum and most frequent speed limit per road category

Units	*[Nominal question: km/h, mph]*

		Maximum speed limit	Most frequent speed limit
	Freeway/Expressway	*[Open-ended question]*	*[Open-ended question]*
	Multilane highway	*[Open-ended question]*	*[Open-ended question]*
	Two-lane rural road	*[Open-ended question]*	*[Open-ended question]*

Road marking characteristics

Evaluate the width, condition, and configuration of the edge lines per road category

		Width (mm)	Condition	How often are the lanes limited by center/edge lines?
	Freeway/Expressway	*[Numerical scale question]*	*[Likert scale, ranging from 1 (very poor) to 5 (very good)]*	*[Nominal question: always, usually, sometimes, rarely, never]*
	Multilane highway	*[Numerical scale question]*	*[Likert scale, ranging from 1 (very poor) to 5 (very good)]*	*[Nominal question: always, usually, sometimes, rarely, never]*
	Two-lane rural road	*[Numerical scale question]*	*[Likert scale, ranging from 1 (very poor) to 5 (very good)]*	*[Nominal question: always, usually, sometimes, rarely, never]*

Examples of condition

Examples of configuration

Lane limited by center and/or edge lines

Lane without edge lines

	Lane without centerline 	*Lane without road markings* 

Connectivity	
Internet users (% of population)	The Global Economy
Mobile network coverage (% of population)	The Global Economy
4G Availability	Open Signal
Average round trip time	Open Signal
DSRC/ITS-G5 availability along main road corridors (WiFi variants for V2X)	*[rating scale question]*
5G Availability along main road corridors	*[rating scale question]*
5G Deployment plan: year for full 5G main roads coverage	*[Closed-ended question]*
Roadside Unit (RSU) deployment status	*[rating scale question]*
Mobile Edge Computing (MEC) availability	*[“Yes” or “no” question]*
Mobile network coverage along main highways	*[rating scale question]*
Use of ITS along main highways	*[rating scale question]*

Working on CAVs integration	
Are you involved in defining policies on CAVs?	*[“Yes” or “no” question] + [Open-ended question]*
Are you involved in defining strategies or plans on CAVs?	*[“Yes” or “no” question] + [Open-ended question]*
Are you collaborating in international actions on CAVs?	*[“Yes” or “no” question] + [Open-ended question]*
In your country, are there National Research Programs and/or Projects focused on CAVs?	*[“Yes” or “no” question] + [Open-ended question]*

Does your organization have an agreement with associations related to CAVs?	*[“Yes” or “no” question] + [Open-ended question]*
Do you know about national public institutions and/or companies involved in CAVs integration?	*[“Yes” or “no” question] + [Open-ended question]*

Smart Roads Classification		
Factors to be considered by the Smart Roads Classification (SRC) **Please indicate how important these factors should be considered by the SRC to enhance the support for automated driving (1: no interested at all, 5: highly interested).**		
	Factors related to physical infrastructure	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Road typology (two-lane rural road, freeway, etc.)* - *Road geometry (horizontal, vertical, cross-section, and visibility)* - *Pavement characteristics (maintenance, roughness, etc.)* - *Intersections and roundabouts* - *Road signage* - *Inventory of barriers* - *Traffic calming devices*
	Factors related to digital infrastructure	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Presence and message of variable message signs, including dynamic restrictions and dynamic speed limits.* - *Signalized intersections* - *High Definition maps* - *Weather information* - *Traffic information*
	Factors related to connectivity	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Possibility to establish V2X communication.* - *5G coverage along the road network* - *Other types of mobile coverage along the road network* - *Deployment of Roadside Units.* - *Availability of ITS solutions for cooperative driving.*
	Additional factors related to automation	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Information about disengagements (when an automated vehicle transfers control to the driver).* - *Information about the environmental conditions (weather, pollution, light conditions…).*

<table>
<tr><td></td><td>Factors related to users</td><td>[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]
- Real-time traffic volume
- Pedestrian count (estimated count within a road segment)
- Real-time existence of slow-moving vehicles, such as bicycles and mopeds
- Real-time warning of stopped vehicles, queues and congestions
- Real-time warning of incidents, accidents or road works ahead
- Adaptive journey planner using real-time road condition data
- Availability of intelligent services in order to facilitate reliable journeys
- Availability of advanced services to facilitate multi-modal journeys planning and adaptive planning in response to real time road status data</td></tr>
<tr><td></td><td>Other factors</td><td>Indicate other factors that you consider important to be included in the Smart Roads Classification. In that case, quantify the important of that factor from 1 -no interested at all- to 5 -highly interested-.</td></tr>
<tr><td colspan="3">Usefulness
The Special Project will develop a framework to provide a classification for smart roads. This project will classify all factors in four dimensions: physical infrastructure, digital infrastructure, connectivity, and automation.
Indicate the level of importance of each dimension for your road administration, from 1 -no interested at all- to 5 -highly interested-.</td></tr>
<tr><td></td><td colspan="2">[Likert scale, ranging from 1 (no importance at all) to 5 (very important)]
- Physical infrastructure (road typology, geometry, pavement, signage, etc.)
- Digital infrastructure (variable message signs, inventory for HD maps, digital signing, weather, and traffic information…)
- Connectivity (capability of the road to support V2I communications, 5G coverage, capacity of cooperative driving, etc.)
- Automation (capacity to support automated driving)</td></tr>
</table>

General comments *[Open-ended question]*

A4.2 Questionnaire 2

International Survey for PIARC Special Project

"Smart Roads Classification"

Questionnaire 2 for Automotive Industry

This questionnaire is part of the PIARC Special Project "Smart Roads Classification", with the support of Universitat Politècnica de València (Spain), that aims at exploring a new framework for the classification of the road infrastructure based on its physical characteristics as well as on its capacity to host automated and/or connected vehicles.

Given that the presence of Connected and Automated Vehicles (CAVs) is on the increase, it is necessary to explore a new Smart Roads Classification (SRC) system that provides information to users and vehicles on their degree of adaptation to automated and/or connected driving. This information should range from indicating which road sections do not allow any type of autonomous driving, to sections that are ready for any autonomous system, going through various intermediate degrees depending on the technology.

This would help users to better know when their level 2+ vehicles would perform more adequately, increasing their user experience and fostering a faster adoption. In order to ensure that the vehicles (CAVs) are perfectly considered in the project, this questionnaire is released to vehicle and component manufacturers (OEMs and TIER1s), with the objective of collecting general information about the current state and priorities of CAVs.

The time required to complete this questionnaire is estimated to average 15-20 minutes per response, without including existing data search.

Response to all questions is not mandatory, but we would appreciate if you could answer, at least, to questions 16 and beyond.

Deadline: April 25th, 2021.

All your responses will be confidential and only for the purpose of the Project. These will be used, in conjunction of the rest of inputs, for the analysis. Therefore, your responses will not be directly incorporated in the final Report. If you agree, we would like to mention your company as collaborator in the final Report and further dissemination.

General questions	
Company	*[Open-ended question]*
Please, could you identify a person within your company who we could contact for any additional information?	
Contact person	*[Open-ended question]*
Role in the company	*[Open-ended question]*
Email	*[Open-ended question]*

Influence of the physical infrastructure on CAVs performance	
Which of these systems for lateral negotiation (ALKS) are being implemented in your vehicles?	[Multiple choice, many answers may apply] - *Lane Departure Warning (LDW)* - *Lane Keeping Assist (LKA)* - *Lane Centering Assist (LCA)* - *Other [Such the case, a new form with open-ended question will show up]*
Which is the minimum speed that your lateral negotiation system (ALKS) can cope with? ***Please indicate the speed and the units (kph/mph)***	*[Open-ended question]*
Which is the minimum lane width that your lateral negotiation system (ALKS) can cope with? ***Please indicate the lane width and the units (m/ft)***	*[Open-ended question]*
Which of the following characteristics apply to your Active Cruise Control systems?	*[Multiple choice, many answers may apply]* - *Full Speed Range 0MPH. The ACC can bring the car to a full stop, and the driver must reactivate it.* - *Traffic Jam Assist/Stop&Go. The ACC can bring the car to a full stop and resume it automatically.* - *Partial cruise control. The ACC turns off when dropping from a minimum speed. The driver must reactivate it when going faster. [Such the case, a new form with open-ended question will show up asking for this minimum speed value.]* - *Other [Such the case, a new form with open-ended question will show up]*
Can your level 2+ vehicles operate at the speed limit along two-lane rural roads? Please indicate the main contributing factors that might trigger disengagements	*[Open-ended question]*
Can your level 2+ vehicles operate at the speed limit along freeways? Please indicate the main contributing factors that might trigger disengagements	*[Open-ended question]*

How should the road markings be to be readable by your driving automation system? Please refer to position (center- / edgelines), width, color and pattern (solid/dashed), maintenance level, readability under the rain, etc.	*[Open-ended question]*
Is your system capable of driving on a road pavement suffering from serious irregularities and eventual potholes? If so, please indicate which kind of irregularities are more likely to affect the system.	*[Open-ended question]*
How is your driving automation system affected by longitudinal cracking sealing or by erased – but still visible – road markings? Please also refer to road orientation and weather conditions, if applicable.	*[Open-ended question]*

Influence of digital infrastructure and connectivity on CAVs performance	
Do your driving automation systems retrieve and use any of these data to support automation?	*[Multiple choice, many answers may apply]* - *Traffic signs from digital maps* - *Variable signs from digital maps* - *Crashes and traffic state (to suggest alternative itineraries)* - *Work zones* - *Other [Such the case, a new form with open-ended question will show up]*
Can your vehicles collect and send any of these data?	*[Multiple choice, many answers may apply]* - *Accidents/Incidents/Conflicts* - *Vehicle performance telemetry* - *Disengagements* - *Other [Such the case, a new form with open-ended question will show up]*
Would your driving automation systems benefit from any of this information received via V2I?	*[Multiple choice, many answers may apply]* - *Information about the road geometry (including curve radius, number of lanes, etc.)* - *Information about traffic operation and road events.* - *Information about the maximum travelling speed according to weather, traffic conditions, or other situations* - *Information for negotiation at intersections.*

	- *Other [Such the case, a new form with open-ended question will show up]*

Smart Roads Classification		
Needs **What of these aspects would be of interest for your autonomous vehicles?**		
	[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)] - *Classification of road segments attending to their readiness to support driving automation and/or connectivity.* - *Physical or variable signs indicating the smart level of the road segment.* - *Tailored digital information about the specific road features that might trigger disengagements of your driving automation system.* - *Digital information about intersection and geometry maneuvers.* - *Others [Such the case, a new form with open-ended question will show up]*	
Factors to be considered by the Smart Roads Classification (SRC) **Please indicate how important these factors should be considered by the SRC to enhance the support for automated driving (1: no interested at all, 5: highly interested).**		
	Factors related to physical infrastructure	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Road typology (two-lane rural road, freeway, etc.).* - *Road geometry (horizontal, vertical, cross-section and visibility)* - *Pavement characteristics (maintenance, roughness, etc.)* - *Intersections and roundabouts* - *Road signage* - *Inventory of barriers* - *Traffic calming devices*
	Factors related to digital infrastructure	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Presence and message of variable message signs, including dynamic restrictions and dynamic speed limits* - *Signalized intersections* - *High Definition maps* - *Weather information* - *Traffic information*
	Factors related to connectivity	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Possibility to establish V2X communication* - *5G coverage along the road network* - *Other types of mobile coverage along the road network* - *Deployment of Roadside Units* - *Availability of ITS solutions for cooperative driving*

	Additional factors related to automation	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Information about disengagements (anonymized, but including, e.g., vehicle model, location, date/time…)* - *Information about the environmental conditions (weather, pollution, light conditions…)* - *Others [Such the case, a new form with open-ended question will show up]*
	Factors related to users	*[Likert scale, ranging from 1 (no interested at all) to 5 (very high interest on this)]* - *Real-time traffic volume* - *Pedestrian count (estimated count within a road segment)* - *Real-time existence of slow-moving vehicles, such as bicycles and mopeds* - *Real-time warning of stopped vehicles, queues and congestions* - *Real-time warning of incidents, accidents or road works ahead* - *Adaptive journey planner using real-time road condition data* - *Availability of intelligent services in order to facilitate reliable journeys* - *Availability of advanced services to facilitate multi-modal journeys planning and adaptive planning in response to real time road status data*
	Other factors	*Indicate other factors that you consider important to be included in the Smart Roads Classification. In that case, quantify the important of that factor from 1 -no interested at all- to 5 -highly interested*

Usefulness **The Special Project will develop a framework to provide a classification for smart roads. This project will classify all factors in four dimensions: physical infrastructure, digital infrastructure, connectivity, and automation.** ***Indicate the level of importance of each dimension for your company, from 1 -no interested at all- to 5 -highly interested-.***

	[Likert scale, ranging from 1 (no importance at all) to 5 (very important)] - *Physical infrastructure (road typology, geometry, pavement, signage, etc.)* - *Digital infrastructure (variable message signs, inventory for HD maps, digital signing, weather and traffic information…)* - *Connectivity (capability of the road to support V2I communications, 5G coverage, capacity of cooperative driving, etc.)* - *Automation (capacity to support automated driving)*

General comments

Suggestions, questions or additional comments.	*[Open-ended question]*
Willingness to mention your company as a collaborator in the final Report and further dissemination.	*[Two-choice question]*

A4.3 Questionnaire 3

International Survey for PIARC Special Project

"Smart Roads Classification"

Questionnaire 3

This questionnaire is part of the PIARC Special Project "Smart Roads Classification", with the support of Universitat Politècnica de València (Spain), that aims at exploring the feasibility of a new framework for the classification of the road infrastructure based on its physical characteristics as well as on its reception capacity of the automation and connectivity of the vehicles.

Given that the presence of Connected and Automated Vehicles (CAVs) is on the increase, it is necessary to explore a new Smart Roads Classification (SRC) system that provides information to users and vehicles on their degree of adaptation to automated driving. This information should range from indicating which road sections do not allow any type of automated driving, to sections that are ready for any automated system, going through various intermediate degrees depending on the technology.

In order to achieve a simple-to-use and rapid-to-implement tool, a first draft for the SRC system has been developed.

The objective of this questionnaire is to collect feedback from all worldwide stakeholders on:

- How do you approach the concept of Smart Roads Classification? What are the challenges and opportunities that you identify?
- How do you rate the criteria and principles that were used to develop this draft SRC system? Do you agree with them?

Your feedback will help us propose a more relevant classification system which would be adapted to different conditions and needs, and to identify challenges and opportunities for road administrations and operators, as well as for the automotive industry.

Relevant background information can be found here:

- **Executive summary**: https://poliformat.upv.es/x/xHnMMF
- Extended document: https://poliformat.upv.es/x/JugYf8

The time required to complete this questionnaire is estimated to average 30-45 minutes perresponse, without including the reading and analysis of the draft proposal for SRC – Executive summary (15 min approx.). Response to all questions is not mandatory, but we would appreciate if you could answer, at least, sections 1 and 2.

In addition, please note that a Webinar on this same topic is organized on June 15th, from 2 to 4 PM (CEST, Paris time).

Who should answer this questionnaire? Decision-makers in road administrations and operators; technicians and consultants in road administrations and operators; managers and technicians of automotive companies; and road specialists from associations, engineering firms, and academia. There may be more than one respondent per organization.

Deadline: June 22nd, 2021

General information

1. Which type of stakeholder do you represent?
   - Road administration/agency: ___
   - Road operator: ___
   - Road association: ___
   - Automotive industry (OEMs, TIER1s): ___
   - Road engineering consulting firm: ___
   - Research institution
   - Academia: ___
   - Another type of stakeholder: ___
2. Name of stakeholder: _________
3. Country: ____________
4. Please, could you identify a person within your institution/company who we could contact for any additional information? (Yes/No)
5. If you answered 'Yes' to question 4, please fill in the following blanks:
6. Contact person: ________________
7. Position: ________________
8. Email: ______________________

Smart Roads Classification – Application and Management

Below you will find some questions related to "how do you approach the concept of Smart Roads Classification?" "What are the challenges and opportunities that you identify?"

9. Do you consider the Smart Roads Classification system necessary for the deployment of CAVs?: Yes/No ________ Why? _____________
10. How may the automotive industry be engaged in the development of the SRC?: _________
11. What is the best way to convey the SRC framework to road users?: __________
12. Should all physical and digital road infrastructure information be shared so that there could be a variety of information providers?: Yes/No.
13. Who should take responsibility for establishing and updating the Smart Road Level (SRL) for every road segment? (More than one option is possible): Road Administration/Road Operator/Automated vehicle/User/Automaker/Shared by all.
14. Who should take responsibility for using the informed Smart Road Level (SRL) for every road segment? (More than one option is possible): Road Administration/Road Operator/Automated vehicle/User/Automaker/Shared by all.

15. What would you prioritize in the road network of your country/region to reach a higher Smart Road Level (SRL)? _______________
16. What benefits and opportunities do you identify about using the SRC? _______________
17. What challenges and barriers do you identify for the deployment of the SRC? ________________
18. Level of understanding of the SRC proposal. You have to rate from 1 -lowest- to 5 -highest-. ____
19. Would you like the SRC system to be deployed in the near future (2030 approx.)? From 1 -totally disagree- to 5 -totally agree-. ____
20. Level of applicability of the SRC in the near future (2030 approx.). From 1 -rarely used- to 5 -widely used-. ____
21. Level of detail accomplished (considering that this draft SRC system aims to explore the feasibility of a new road classification). From 1 -insufficiently detailed- to 5 -very detailed-. ______
22. Do you agree with the proposed objectives for the SRC?

Objective	Yes	No	Comment
Common language, to facilitate communication between all stakeholders			
Useful, to facilitate the application by Road Administrations or road operators			
Universal, to be applicable to roads worldwide and to all types of roads			
Standardized, to ease its development and implementation			
Interoperable, to facilitate data exchange			
Robust, to provide an adequate and coherent smart level for every road segment			
Consistent, to facilitate adequate messages for users			
Simple, to ensure understanding for users			
Integrable, to facilitate the necessary transition from the current classification systems			
Dynamic, to reduce the assigned intelligent level after sudden variations in environmental and operational factors			
Flexible, to be quickly and easily adaptable to technological advances and sudden variations in technology operation			
No liability for the road administration or road operators			

23. Indicate other objectives that you consider important to be included in the Smart Roads Classification: ____________________
24. Do you agree with the following proposed KPIs?

Some Key Performance Indicators (KPIs) have been proposed to know the performance situation of the road network and make strategic decisions, maximizing the outcome of investments. The KPIs can also be used to compare the situation of a road network longitudinally (i.e., over time) and the road networks among countries or regions, that is, the success of what are they meant to measure.

KPI – Key Performance Indicators	Yes	No	Comment
Disengagement rate per road segments of each smart road level, for the entire road network (disengagements/km or mi.)			
Average Crash Rate involving CAVs for the entire road network			
Percentage of each smart road level for the entire road network			
Percentage of each smart road level for every road type network			
Percentage of each ISAD level for the entire road network			
Percentage of each ISAD level for every road type network			
Percentage of each LOSAD level for the entire road network			
Percentage of each LOSAD level for every road type network			

25. If you consider other KPIs to be included, please suggest them: ______________________
26. Please, provide your feedback about how to apply the SRC at the planning and investment stage: _________________________
27. Please, provide your feedback about how to apply the SRC at the management stage: _________

Smart Roads Classification – Proposal

Below you will find some questions related to criteria and principles that were used to develop this draft SRC system. “Do you agree with them?”

28. Please, relate the current road typology classification system to the maximum Smart Road Level (SRL) expected in the near future (2030 approx.).

    SRLs from the lowest to the highest level:

    Humanway (HU) - Assistedway (AS) - Automated way (AT) - Full Automated way (FA) - Autonomous way (AU)

Typology	2030				
	HU	AS	AT	FA	AU
Motorway					
Freeway/Expressway					
Multilane highway					
Two-lane rural road					

29. Please, relate the current road functionality classification system to the maximum Smart Road Level (SRL) expected in the near future (2030 approx.).

    SRLs from the lowest to the highest level:

    Humanway (HU) - Assistedway (AS) - Automated way (AT) - Full Automated way (FA) - Autonomous way (AU)

Functionality	2030				
	HU	AS	AT	FA	AU
Freeway					
Arterial					
Collector					
Local					

30. What do you expect in the near future (2030 approx.) about the percentage of every Smart Road Levels (SRL) for all the road network in your country?

Year	HU	AS	AT	FA	AU
2030					

31. Do you think it is necessary for manufacturers to make their ODDs explicit in order to serve as a basis for the determination of Operational Road Sections (ORSs)?: Yes/No.
32. If you answered ‘Yes’ to question 31, please, suggest how to proceed: _______
33. Should automated vehicles be required to report their disengagements?: Yes/No.
34. If you answered ‘Yes’ to question 33, do you think the collection and analysis of disengagements of automated vehicles should be open access?: Yes/No.
35. If you answered ‘No’ to question 33, please, include your comments and suggestions:

    ____
36. Do you agree with the number (5) of smart road levels: Yes/No

37. If you answered ‘No’ to question 36, please, suggest another number: _______________; and the main properties for each level: __________________

38. Do you consider appropriate the SRC to be obtained by combining the indicators “Infrastructure Support Levels for Automated Driving” (ISAD) and “Level Of Service for Automated Driving” (LOSAD)?: Yes/No

39. If you do not agree with these indicators, please explain why: ____; and, suggest alternatives: _____

40. Do you agree with all factors considered for estimating the LOSAD (Level Of Service for Automated Driving)?:

Layer	Factors	Yes	No	Comment
Physical Infrastructure	Operational Road Section (ORS)			
Digital Infrastructure	Disengagements			
Digital Infrastructure	Weather – Visibility			
Digital Infrastructure	Weather – Snow/Icy pavement			
Digital Infrastructure	Weather – Rainfall intensity			

41. If you consider other factors to be included for LOSAD estimation, please suggest them: _______________

42. Do you agree with all factors considered for estimating the ISAD (Infrastructure Support Levels for Automated Driving)?:

Layer	Factors	Yes	No	Comment
Digital Infrastructure	Digital map			
Digital Infrastructure	Digital map update frequency			
Digital Infrastructure	Road traffic and events ahead			
Digital Infrastructure	Weather conditions			
Digital Infrastructure	Variable speed limit			
Digital Infrastructure	Traffic lights			
Digital Infrastructure	Traffic performance information			
Digital Infrastructure	Microscopic dynamic driving guidance			
Digital Infrastructure	Presence of Roadside Units (RSUs)			
Digital Infrastructure	Sensors for trajectories of vehicles and users			
Digital Infrastructure	Automatic road data processing			
Digital Infrastructure	Positioning accuracy			
Connectivity	DSRC/ITS-G5 – Availability			
Connectivity	C-V2X (5G) – Availability			
Connectivity	DSRC – Range			
Connectivity	Reliability			
Connectivity	AV Throughput			
Connectivity	Latency			
Connectivity	Signal strength			

43. If you consider other factors to be included for ISAD estimation, please suggest them: _____________

General comments

44. Let us know any suggestion, question or additional comment that you consider important in the framework of this project: ________________

If you want to be mentioned in the final SRC Project Report, please fill in the following blank with the exact name you would like to appear (names of all respondents to this questionnaire will be published in the final SRC Project Report): ________________

World Road Association (PIARC)

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