D7.3 Roadmap: Holistic pathway towards CAVs

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Executive summary

Connected Automated Vehicles (CAVs) could significantly reduce the number of serious injuries and fatalities, but for that to happen, we need to develop robust and holistic solutions that ensure the effective integration of safety measures targeting all road users: drivers, vehicle occupants, and of course our most Vulnerable Road Users (VRUs), pedestrians, cyclists and motorcyclists.

SAFE-UP (proactive SAFEty systems and tools for a constantly UPgrading road environment) is a Research and Innovation Action funded under the Horizon 2020 programme with the aim to proactively address the novel safety challenges of future mobility systems through the development of tools and innovative safety methods, leading to remarkable improvements in road transport safety.

One of the objectives of WP7 is to ensure effective exploitation of the project results. To that end, the main objective of this deliverable is to identify, in a holistic way, the main drivers, barriers and breakthroughs that will enable the revolution promised by the predicted benefits of autonomous driving, enabling a successful impact of SAFE-UP's developments. Impacts and challenges of CAVs are presented under a classification of five key pillars (vehicle technology, infrastructure, regulations, user approach and business models), strongly related among themselves as concluded in chapter 8 (holistic approach). A brief description of the current status and the challenges for each pillar is provided, ending with a selection of the main break points (as milestones) that would bring developments forward.

To complete this roadmap, we have benchmarked several European reference documents, including other recent roadmaps from EU networks, market studies and consultancy reports, among others. The methodology has also included dedicated interviews with experts, both from inside and outside the SAFE-UP consortium, specialized in the different five pillars. After completing this document, the authors realized that providing conclusions beyond each of the five pillars, was something missing in existing literature. Therefore, the final chapter integrates recommendations under a holistic approach, depicting synergies between the different pillars, as well as framing them under specific timelines.

This roadmap is the starting point of a process that will be continued during project implementation, with regular updates including latest news and developments affecting challenges and impacts, and will be completed with the submission of two related deliverables under this same WP7 (D7.5 – Position paper, D7.6 – Exploitation results and business cases of SAFE-UP developments), both due in project month 36 (May 2023).

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List of abbreviations

Abbreviation	Meaning
ACC	Adaptative Cruise Control
AI	Artificial Intelligence
AV	Autonomous Vehicles
AD	Autonomous Driving
ADAS	Advanced driver-assistance systems
CA	Consortium Agreement
CAGR	Compound Annual Growth Rate
CAV	Connected Automated Vehicles
CBA	Cost-Benefit Analysis
CCAM	Cooperative and Connected Automated Mobilty
CCAV	Cooperative and Connected Automated Vehicle
C-ITS	Cooperative Intelligent Transport Systems
D	Deliverable
DDT	Dynamic Driving Task
DSRC	Dedicated Short-Range Communications
EC	European Commission
EPO	European Patent Office
ERTRAC	European Road Transport Research Advisory Council
Euro NCAP	European New Car Assessment Programme
FOT	Field Operational Trials
GA	Grant Agreement
GRVA	Working Party on Automated/Autonomous and Connected Vehicles
HMI	Human-Machine Interface
ISAD	Infrastructure Support Levels for Automated Driving
ITS-G5	European standard for vehicular communications based on the IEEE-802.11p or extended IEEE 802.11bd standard
LiDAR	Light Detection and Ranging
ML	Machine Learning
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
OTA	Over-the-AIR
PM	Person Month
PPS	Points per Second
R&D	Research and Development

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SAE	Society of Automotive Engineers
SC	Steering Committee
SRIA	Strategic Research and Innovation Agenda
STRIA	Stratefic Transport Research and Innovation Agenda
SotA	State-of-the-Art
T	Task
UNECE	United Nations Economic Commission for Europe
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
VRU	Vulnerable road user
WP	Work Package

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1. Introduction

1.1 Description of the SAFE-UP project

Progress on reducing road fatalities in Europe has slowed in recent years and the EU's mission to halve the number of road deaths by 2030 could be in jeopardy if this trend is not reversed. Currently, over 90% of road accidents are caused by human error (Euro NCAP, 2017). To reduce traffic collisions and casualties, future mobility systems will rely on partially and fully automated vehicles to remove causal factors like driver distraction, fatigue or infractions and by reacting autonomously to emergency situations.

Connected Automated Vehicles (CAVs) could significantly reduce the number of serious injuries and fatalities, but for that to happen, we need to develop robust and holistic solutions that ensure the effective integration of safety measures targeting all road users: drivers, vehicle occupants, and of course our most Vulnerable Road Users (VRUs), pedestrians, cyclists and motorcyclists.

SAFE-UP (proactive SAFEty systems and tools for a constantly UPgrading road environment) is a research and innovation project funded by the Horizon 2020 programme which aims to proactively address the novel safety challenges of future mobility systems through the development of tools and innovative safety methods, leading to remarkable improvements in road transport safety.

On the road to future mobility, we will see an evolving mix of automated, conventional and new micro-mobility vehicles. With the coming changes to transport modes and vehicle behaviour, new risks will emerge from the novel interactions among all road users - 4-wheeled vehicles and VRUs. SAFE-UP studies these impending road safety challenges to create holistic solutions aimed at maximising the expected safety benefits of automation and connectivity. By integrating existing accident data with future traffic conditions and applying a new toolkit of safety metrics and sub-microscopic simulations of vehicle-to-vehicle and vehicle-to-VRU interactions, SAFE-UP will proactively identify future safety-critical scenarios among different road users, environments and vehicles, to prioritise the development of active and passive safety system prototypes integrated into demonstrator vehicles.

Rounding out this holistic approach, SAFE-UP will produce targeted education, training and awareness schemes for fostering the safe integration of automated driving functions, including new traffic participation behaviours, correct use of safety technology, adoption of connected functions for VRUs, and hazard perception in future safety-critical scenarios. Dedicated training programmes will then be developed for drivers, riders, cyclists and pedestrians.

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1.2 Motivation of the document

Despite the initial hype around CAVs, partly related to automakers broadly promoting ambitious plans for future automated vehicles, some of these announcements have been proven premature. After having invested billions of euros in R&D, delivery on most announcements has been postponed or even cancelled. OEMs claim that technological hurdles and the lack of sufficient regulations are causing these changes (McKinsey, 2020).

There is no doubt that CAVs will instigate a whole new revolution in transportation that will impact a lot of different areas, not only on the road. Autonomous vehicles are not (only) a transportation issue but an everything issue, but unfortunately very few professionals are working on their market introduction with such holistic approach, and that is affecting the CAVs timeline: academia may lack a global perspective, policy-makers are usually not aware of latest technological developments and trends and public and road authorities, in general, often wonder what is needed to improve their network and to embrace the potential benefits of vehicle automation, and who will make all the necessary investments.

Since the very first moment we defined this deliverable, we've always wanted to contribute to this transition, producing something unique, that could complement the existing literature and knowledge available. Therefore, the main motivation behind this deliverable is to identify, in a holistic way, the main drivers, barriers and breakthroughs that will enable the revolution promised by the predicted benefits of autonomous driving. To this end, several European reference documents have been reviewed so we could build upon the main drivers, barriers and breakthroughs already identified or forecast by technology developers, vehicle manufacturers, RTOs, policy-makers, investors, and many other relevant stakeholders within the CAV domain. Our benchmark has encompassed a long list of State of the Art documents analysed (see section 10 for further details), including, among others:

- Strategic Research and Innovation Agenda (CCAM, 2021)
- Connected Automated Driving Roadmap (ERTRAC, 2019)
- Connected, Cooperative and Automated Mobility Roadmap – Draft (ERTRAC, 2021)
- Safe Road Transport Roadmap (ERTRAC, 2019)
- Euro NCAP 2025 Roadmap – In pursuit of Vision Zero (Euro NCAP, 2017)
- STRIA Roadmap on Connected and Automated Transport (European Commission, 2019)
- UK Connected and Automated Mobility Roadmap to 2030 (Zenzic, 2020)
- ARCADE D2.1: CAD consolidated roadmap Year 1 (Rosenqvist, 2019)

After a thorough analysis of the main challenges, the goal was to classify them into what we have called "pillars". Even though most of the documents try to distinguish between main areas as well ("*Clusters*" for CCAM, "*Thematic areas*" for ARCADE, "*Key challenges and objectives*" for ERTRAC, "*Themes*" for Zenzic), we believe the classification could be

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simplified, as some of the areas overlap with common challenges and interests, so there could be merged. Consequently, this roadmap is structured into five “pillars”:

- Vehicle technology: touches upon the most important and necessary technologies that vehicles need to integrate so they can drive safely and efficiently, delivering all the benefits they have long promised.
- Infrastructure: requirements and adaptation needed to our roads to enable the introduction of CAVs.
- Regulations: role that policymakers need to undertake to ensure a safe and efficient introduction of CAVs.
- User approach: overview of the main challenges and milestones that users and citizens face, and how to foster high user acceptance of CAVs to ensure widespread adoption.
- Business Models: twofold approach. On the one hand, it describes the main socio-economic impacts that CAVs could bring as a reason to justify their introduction and the potential need to finance them. On the other hand, it gives an overview of the main challenges in making the whole ecosystem sustainable to ensure long-lasting positive effects

Each pillar is assigned to a dedicated chapter including three sections; firstly, we present a brief overview of the main categories of the pillar, covering the current situation and State of the Art in each of them; secondly, the main challenges and key priorities are described, in order to inform future research directions and development areas; lastly, we highlight the key tipping points (breakthroughs), those milestones that will represent huge steps on this journey to road transport automation when eventually achieved,.

An effective introduction of CAVs cannot happen if one of these pillars fails. However, these pillars are unlikely to evolve in parallel. For obvious reasons, some need to evolve first so the others can follow later. Despite their varying rates of development, these pillars interact with each other in non-linear ways. In fact, different development stages from one pillar retrofit other pillars, and in the end, they advance all together in a holistic way, creating an effective pathway towards CAVs.

Vehicle technology would be the first. If CAVs are unable to meet the expectations and deliver the impacts that they are supposed to, then the whole discussion about vehicle automation and its benefits is meaningless. On the other hand, research suggests that an effective introduction of CAVs cannot happen if the infrastructure is not adapted - both physical and digital. Additionally, although vehicles would be capable of driving thanks to their advanced features and a sufficiently upgraded infrastructure, a proper regulations framework needs to be in place allowing them to drive, subsequently enabling effective implementation and widespread adoption – otherwise we would be hindering again the potential benefits of CCAM.

Finally, even if CAVs can drive on our roads and allowed to do so by the appointed regulatory bodies, user acceptance for these new vehicles needs to prove high, otherwise we cannot

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ensure that the adoption will be wide, and the benefits won't be forthcoming. In addition, the current situation could worsen, especially concerning road safety and traffic efficiency, if users cannot interact with CAVs, or are not capable to maximise their benefits, Moreover, if adoption is not high, it is very likely that the vehicles won't be financially viable, hindering again the widespread adoption.

Most of the documents aforementioned shape the challenges and R&I directions in a descriptive way (bullet points), but they often lack an overview of how the different areas connect. To overcome this, a holistic approach is outlined at the end of the document (chapter 8), with the aim to show the main connections between the five pillars. This is key to ensure we address the different pillars all together from the beginning, enabling a smooth transition to automation and an effective introduction of CAVs. In it is vital that. That way we can introduce the changes gradually but effectively and avoid chaotic and dangerous situations similar to those that occurred after the introduction of cars at the beginning of the 20th century, like unexperienced drivers, unclear traffic rules, insufficient infrastructure, and lack of regulations (Loomis, n.d.).

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2. The path towards vehicle automation

2.1 The reasons behind vehicle automation

Transport operators and citizens are facing what some are calling mobility's second great inflection point (Dhawan et al., 2019). Several factors are playing a role in this and are bringing about a situation that will not leave our roads unchanged.

With the rapid population growth in the last century and recent decades, regions today face high urbanization rates, with more people living in urban areas. In 2018, the USA had 82% of its population living in urban areas, and Europe had around 74%. Levels were lower in Asia (50%) and in Africa (43%), where a majority still lived in rural areas. However, the trend shows that by 2050, 68% of the world population will be living in urban areas, combined with the overall growth of the world's population, that could add another 2.5 billion to them by 2050 (UN, 2018).

As this urbanization keeps growing, sustainable development depends on an appropriate management of resources, including housing, transportation, energy systems as well as other services like education or health care. Nevertheless, this is not always considered, or the efforts are not sufficient. For example, because of the increased number of cars in cities, we have already observed how congestion rises in urban road networks, coupled with the preoccupying problem of emissions, safety, health, lack of urban space, etc.

To support the introduction of connected, cooperative and automated vehicles, it is important to define the potential impacts they could bring to transport and society. There are many studies that have tried, from different angles, to define and categorise their impacts.

A good example is the deliverable D3.1 from the H2020 project LEVITATE[1]. In it, a taxonomy of potential impacts of CCAVs is presented at different levels of implementation. An interesting remark is the distinction made between direct, systemic and wider impacts (Elvik, 2019).

Direct impacts refer to changes noticed by each road user on each trip. Such impacts mainly include travel time and its value, travel comfort, vehicle operation and ownership cost, and access to travel.

Systemic impacts are impacts happening within the transport system. Impacts of this kind include road capacity, road safety, congestion, infrastructure wear, infrastructure design, modal split, vehicle ownership and utilisation rate, parking space, and traffic data availability used for transport planning.

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[1] https://levitate-project.eu/

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Wider impacts deal with changes occurring outside the transport system, but affected by it, such as changes in employment and land use, trust in technology, energy efficiency, vehicle emissions, air pollution, public health, inequality in transport, and public finances, among others.

However, road safety benefits that CCAVs promise to bring to our roads are, without a doubt, one of the greatest reasons to invest in this technology and the main reason that is powering SAFE-UP. In the EU, even though the underlying trend of road fatalities is moving downwards, progress has slowed in most countries since 2013, and the target of "Vision Zero" by 2050, where road fatalities will be completely eradicated, it is unlikely to be met.

Given that around 90% of road accidents are caused by human errors (Euro NCAP, 2017), higher automation levels show enormous potential safety benefits, assuming that the vehicle is more capable than the human driver in complex situations. However, it is also necessary to ensure that AVs don't introduce new safety threats in our roads, and if they do, it is important to characterise them and evaluate their risk. Some early results from Waymo (Schwall et al., 2020) suggest that changes in crashes are already happening due to automation. From 6.1 million miles of fully automated driving (includes trips with a safety driver, driverless trips, and simulated), only 47 lower severity events occurred. Also, it has to be remarked that the vehicle did not have any events that involved road departure, contact with the roadway environment, infrastructure or other fixed objects, or rollover, a single-vehicle collision typology from the NHTSA, that accounts for 27% of all US road fatalities. There were also no collisions in which the Waymo vehicle struck a cyclist or pedestrian.

In addition, automated and connected mobility will play an increasing role, together with smart traffic management systems enabled by digitalisation. The EU transport system and infrastructure will be upgraded to support new sustainable mobility services that can reduce congestion and emissions (European Comission, 2019), by means of improved traffic efficiency.

Autonomous vehicles could also contribute to an improved transport ecosystem. Most specially for people with special needs, not owning a car, or no driver license (in the case of the highest automation level). Also, when higher automation levels will allow the driver to safely transfer the driving task completely to the vehicle, this will improve the value of travel time, as the driver will be able to dedicate it to other tasks. To this regard, two of the most promising use cases for the short term are the "traffic jam chauffeur" and "highway pilot" (ERTRAC, 2019), both for their promising user acceptance and technical viability given the current State of the Art.

Vehicle automation also has the potential to improve logistics efficiency and cost reduction. One example is truck platooning, one of the most promising use cases for the early introduction of automation (Skoglund et al., 2019). This could also contribute to alleviate the driver shortage of around 20% in 2019, a concerning issue brought up by the European Transport Workers Federation (ETF) and the International Road Union (IRU) (IRU, 2020).

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Finally, CAVs promise to increase the automotive sector competitiveness and bring a positive economic impact. Some studies show that sales of passenger vehicles could exceed 550 billion EUR by 2050 in the EU, nudged by the introduction of automation increasing travel activity due to reduced costs of driver's time, new user groups and new mobility business models (Alonso Raposo et al., 2021). The automotive sector will not be alone in benefiting from the introduction of CCAVs, other sectors like electronics and software, telecommunications, freight transport, insurance, maintenance, data services, digital media, and power, will also be impacted (Alonso Raposo et al., 2018).

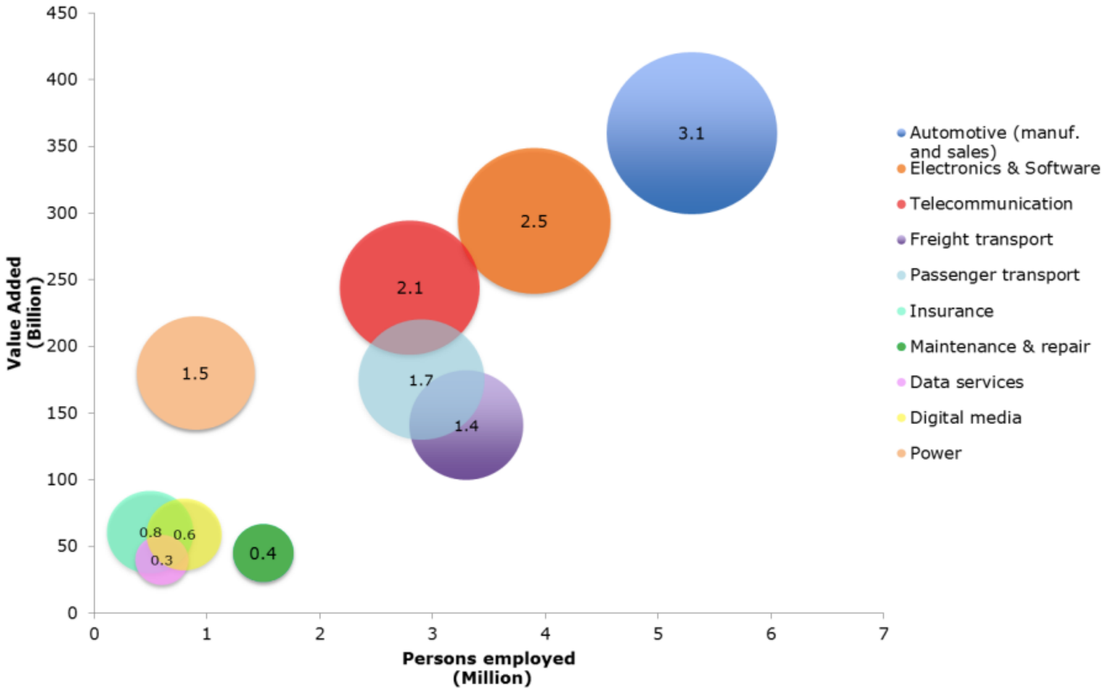

Figure 1: State of the main sectors affected by CCAM, showing value added, persons employed, and share of gross value added in the total EU-28 (Source: Alonso Raposo et al., 2018)

Having observed the main issues surrounding urban environments and transport systems, this suggests that it is the right moment for CCAM to be launched, as three trends seem to be converging at the same time: environmental impact, connectivity and ride-hailing, and CAVs (Madrigal, 2018).

2.2 Levels of automation and Operational Design Domain (ODD)

As self-driving vehicles start populating our roads and become a reality, the need to classify them increases. As countless videos of sleeping or distracted drivers appear, consumers and policy makers are confused about what comprises autonomous driving and what does not.

To establish agreed-upon standards in the first phases of the transition to autonomous vehicles, the Society of Automotive Engineers (SAE) published a taxonomy in 2014 to classify

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the degree of self-driving capability, the role the driver has, and the Operational Design Domain (ODD) where the vehicle is capable of driving autonomously. Six different levels (from zero to five) have been identified, ranging from vehicles without self-driving technology to fully automated vehicles.

Level 0 means that the vehicle has no automation technology. The driver is always entirely in charge of operating the vehicle, including braking, accelerating, steering, parking or any other necessary movement. However, driver support systems may be present, like stability control, automatic emergency braking, forward-collision warning, and blind-spot warning.

At Level 1, the vehicle has at least one driver support system that provides braking/ acceleration assistance or steering assistance. The driver remains responsible and must be ready to take back control at any time and for any reason. Adaptative cruise control is an example of Level 1 automation, where the vehicle is capable of following a safe distance between itself and the traffic ahead. A lane-centring or lane-following assistance would also qualify as Level 1. However, a vehicle combining both of these features simultaneously would be considered a Level 2.

Level 2 vehicles can take over steering, acceleration, and braking in specific scenarios. However, the driver must remain alert and is required to always supervise the system.

There is a big leap from Level 2 to Level 3. Level 3 is known as conditional driving automation. It uses a combination of driver assistance systems and decision algorithms to adapt to driving situations around the vehicle. If the ODD conditions of the vehicle are met, the driver doesn't need to supervise unless it is requested, for example in the case of an emergency due to system failure.

Level 4 does not require any human interaction in the vehicle's operation when the ODD conditions are met. This means, that if any emergency should happen, the vehicle will stop itself and set to a safe status. This is the case of automated driverless taxis and public transport services, where vehicles are programmed to make trips in specific geographical areas that meet certain conditions, like traffic or weather, among others.

Level 5 means the vehicle is capable of driving autonomously in every place and in all conditions (ODDs), without any human interaction.

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Table 1: Levels of driving automation according to SAE J3016 standard (Source: SAE, 2021)

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	You are driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			You are not driving when these automated driving features are engaged – even if you are seated in “the driver's seat”		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	No system	“Feet-off”	“Hands-off”	“Eyes-off”	“Brain-off”	No driver
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/ acceleration support to the driver	These features provide steering AND brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		These features can drive the vehicle under all conditions
Example features	- automatic emergency braking - blind spot warning - lane departure warning	- lane centring OR - adaptative cruise control	- lane centring AND - adaptative cruise control at the same time	- traffic jam chauffeur	- local driverless taxi - pedals/ steering wheel may or may not be installed	- same as L4, but feature can drive everywhere in all conditions

Having said this, and as expressed in SAE standard J3016, conceptually, the role of a driving automation system in relation to the user in undertaking part of or the whole dynamic driving task (DDT) depends on the specific conditions under which it performs that role (Figure 2). These “conditions” form what is called the Operational Design Domain (ODD). For example, certain Adaptative Cruise Control (ACC) systems may be intended to operate only at high speeds, only at low speeds, or at all speeds. Level 1 through 4 expressly consider ODD limitations, in contrast to Level 5 or Level 0, which are not subject to it (SAE, 2021).

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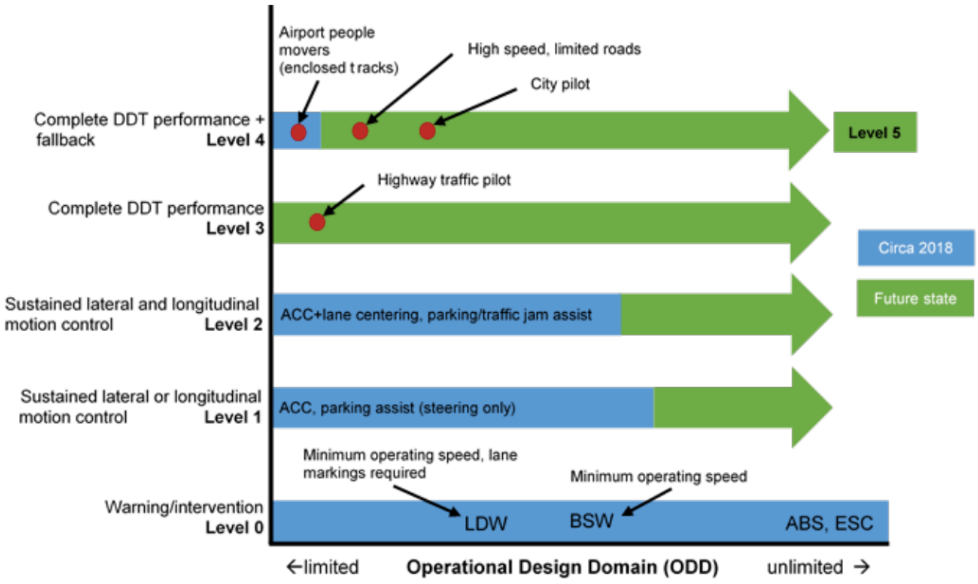

Figure 2: ODD relative to driving automation models (Source: SAE, 2021)

ODD for a certain AD feature encompasses a broad set of parameters that define the limits of that feature. It includes variables as widely ranging as specific road types (rural, urban, highway, etc.), weather conditions (rainy, foggy, snowy, etc.), lighting conditions, geographical restrictions, and the presence or absence of certain road features, such as lane markings, roadside traffic barriers, median strips, etc.

Accordingly, accurately describing a feature, requires both identifying its level of automation and its Operational Design Domain (ODD).

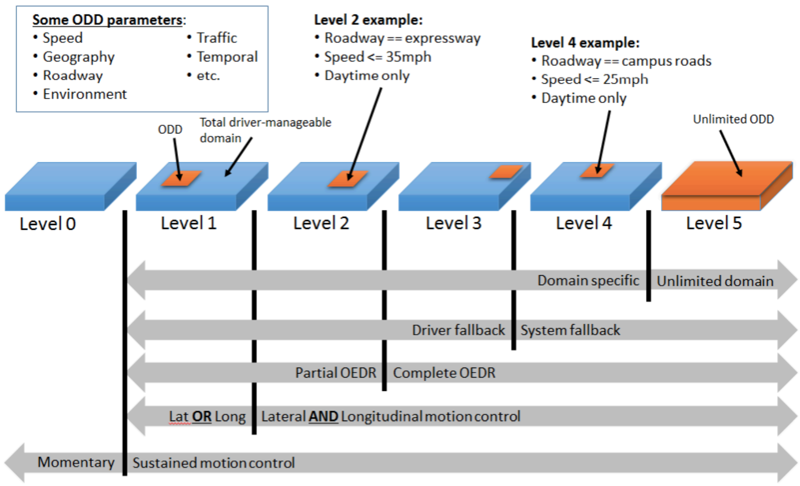

Figure 3: ODD relative to driving automation levels (Source: SAE, 2021)

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3. Vehicle technology

This pillar focuses on the development of technologies embedded in connected and automated vehicles (CAVs) that allow it to perceive the environment and take decisions, while ensuring comfort of occupants and safety of all road users.

This is one of the pillars that received the most funding and has been in the pipeline of researchers. For this reason, it's probably the area where developments are more advanced, and in-fact the European Patent Office (EPO) has registered a growth 20 times faster in self-driving vehicle technologies compared to other technologies in recent years. From 2011 to 2017, patent applications at the EPO increased by 330%, compared to 16% across all technologies in the same period (EPO, 2018). In the same line, investment activities in AV technology have also increased by approximately 900% between 2014-2019 compared to 2010-2013, very much in contrast to other fields in the automotive sector (Möller et al., 2019).

Most stakeholders, agree that the technology is already available for the vehicles to drive autonomously, and several pilots and experiments demonstrate so. Nevertheless, despite these advances, several challenges remain if we want to make automation a reality, ensuring the systems are safe, reliable, resilient, efficient, and widely accepted.

3.1 Where are we today?

The way CAVs operate, is often defined as the "sense-think-act" chain. The vehicle technology relies on a perception system based on sensors and connectivity, and an internal processing system that digests the information provided by perception to generate an accurate and generic scene representation of the vehicles' surroundings.

In this chapter, a brief description of the main parts forming the vehicle technology to enable self-driving will be explained, along with the challenges they bring and what major steps would be needed to advance on the road to automation.

<u>Sensors</u>

The development of sensors is key to make automated driving a reality. Sensing is crucial to reliably identify, follow, and differentiate between objects in the road, under the full range of locations and environmental conditions in which the vehicle is intended to operate. To do so, vehicles use different sources (including radar, lidar, ultrasonic sensors, cameras, etc.).
Cameras allow the vehicle to see objects as humans do and interpret/classify them. However, they are strongly affected by the weather conditions such as rain or fog. In addition, if images aren't good enough (e.g., because the colour of the objects is very similar to the background, or the contrast is low), perception algorithms can fail as well.

On the other hand, radar (Radio Detection and Ranging) uses radio waves to detect objects and gauge their distance and speed in relation to the vehicle in real time. The strong point

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about them, is that measurements are not considerably affected by adverse weather conditions. However, it is not capable of classifying objects, and pedestrian detection is not always high enough to ensure safety on the road. Further, 2D radars are still widely used, and they have some trouble to determine accurately an object's height, as the scanning is done horizontally. Currently, 3D radars are being developed to overcome this barrier.

LiDAR (Light Detection and Ranging) sensors use laser instead of radio waves. Apart from measuring distances, some models can create 3D images that can cover 360º around the vehicle. Similarly to cameras, snow or fog can block their detection and negatively affect their performance.

To have a complete, reliable, and safe perception of the environment, these different sensors can be aggregated using "sensor-fusion". It also ensures some level of redundancy to compensate for the weaknesses of each sensor type and in case a component fails. In addition, locating the vehicle in this perceived environment is very important as well, via advanced digital mapping technologies. The first big challenge is to achieve a balanced "sensor-fusion" to enable safe driving in all conditions with expanded ODDs, considering more extensive safety requirements for extended ODDs. SAFE-UP's Demo 2 is working on quantifying the effect of bad weather conditions on cameras, radars, and LiDAR, in order to have a more balanced sensor configuration capable to compensate and adapt to different situations.

The second major focus should aim at lowering the cost of sensor suites while ensuring the availability of high-precision components. More specifically, LiDAR cost will be one of the main drivers for the affordability of CAVs, allowing automakers to benefit from economies of scale.

In fact, some OEMs, like Tesla, even decided not to include this technology in their vehicles to keep production costs down, a decision that encountered much criticism, saying that it is not responsible to eliminate this technology if safety is to be guaranteed in higher automation levels. More than that, company announcements claimed that the vehicle is capable of measuring depth without LiDAR, relying only on cameras (Tesla, 2019). However, to achieve this, large amounts of data are needed to train deep learning algorithms and AI working on powerful computer systems.

On the other hand, some opinions seem to counter this, suggesting that the technology behind LiDAR is quite simple, and it shouldn't cost much (Madrigal, 2018), so when there is demand volume, the price will drop. To this extent, some studies projected an impressive CAGR (Compound Annual Growth Rate) of 12,5% for the global LiDAR market size over the period of 2021 to 2031 (Fact.MR, 2021). In fact, in the last years, LiDAR prices have dropped considerably, however not as a result of mass-production volumes but due to the strategies of different manufacturers.

Moreover, one study (Rangwala, 2020) has made an attempt to *quantitatively* evaluate the price of LiDAR (Figure 4) based on two KPIs: range (R) and points per second (PPS). Range defines the maximum distance that the LiDAR can reliably provide information. PPS defines

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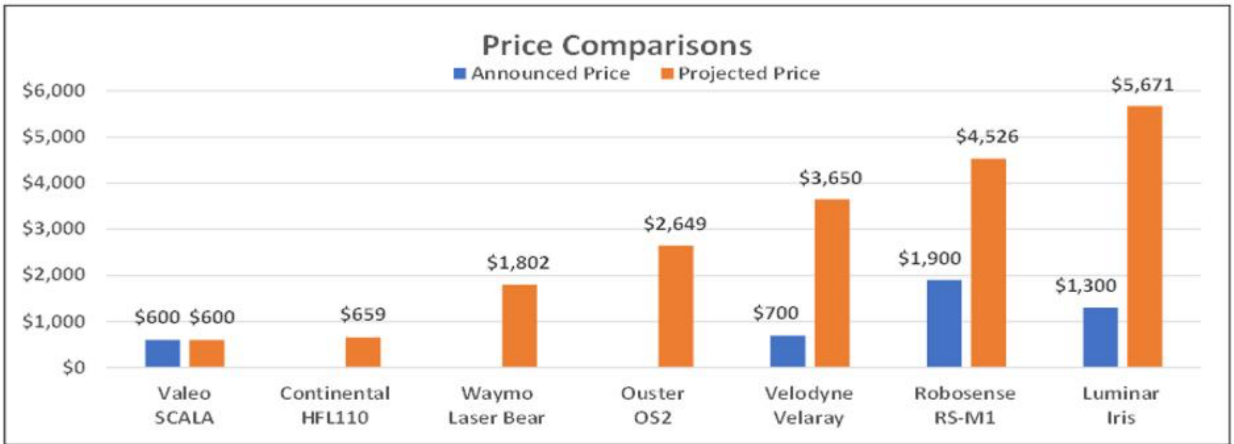
how many pixels the LiDAR can generate in an image every second. The study made some inference on expected prices based on their performances and compared those to the prices communicated by the respective manufacturers. An interesting finding was that in some cases, the announced price was much lower than the calculated price. This suggested that the price not only depends on its performance, but also on the software and hardware configuration mix, innovations in design, and scaling of the bill-of-material (BOM) and manufacture.



R (m)	60	50	30	120	200	150	250
PPS (K/s)	60	100	513	650	800	1125	1200
P	1.0	1.1	3.0	4.4	6.1	7.5	9.5

Figure 4: LiDAR price comparison in relation to Range (R) and points per second (PPS) (Source: (Rangwala, 2020))

In summary, the right balance between sensor accuracy, robustness, reliability, and its cost, still remains to be found, while keeping an eye on technology developments and market factors that will also influence the price.

<u>Automated driving systems</u>

The automated driving system is the core of the driving task. A general abstraction of the (Claussman et al., 2020) hierarchical scheme of autonomous driving is shown in Figure 5. The input data for the motion strategy includes data from the ego vehicle, obstacles, and infrastructure, obtained from the perception, localisation, and communication (vehicle-to-X, V2X). This data is merged to form a “scene representation”, providing a map with obstacles, lanes, traffic, road, and ego vehicle information.

On the other hand, the control block is fed with the intended motion, in order to act on actuators to move the vehicle. The control block forms a closed loop with the motion strategy block, to provide an up-to-date ego vehicle status, so that the motion strategy remains accurate (Claussman et al., 2020).

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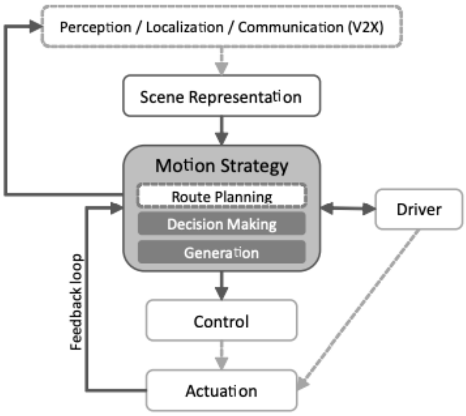

Figure 5: A hierarchical scheme of Autonomous Ground Vehicle systems (Source: (Claussman et al., 2020))

Claussman et al. (2020) also distinguish between five main functions in the motion strategy hierarchy, as can be seen in Figure 6.

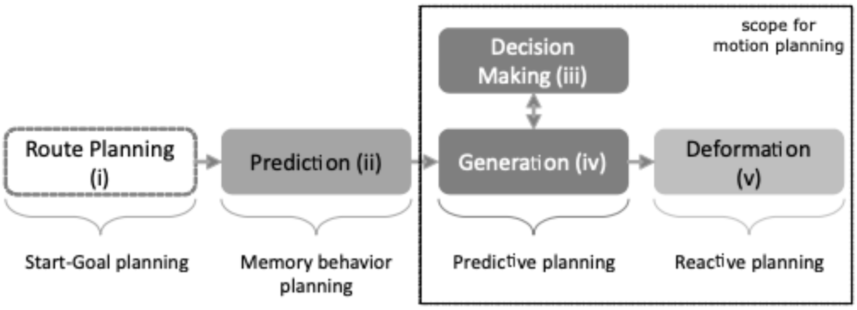

Figure 6: Motion planning five main functions (Source: (Claussman et al., 2020))

The route planning (i) acts as a trip scheduler, providing a long-term plan from the origin to the desired destination.

The prediction function (ii) stores the current and historic dynamics data to predict the dynamics of all the elements surrounding the ego vehicle. The hardest task is to predict obstacles' behaviour, more specifically, the other vehicles and VRUs.

The authors considered that the main scope of the motion planning is formed by the decision making (iii), generation (iv), and deformation (v). These use two approaches. The first one is a high-level predictive planning built around risk evaluation, criteria minimisation, and constraint submission, used to select the best solution (iii) out of the generated (iv) candidates. The second one is a low-level reactive planning deforming the previously generated motion. Naturally, predictive planning is more time-consuming than the reactive one, because it acts on a larger range of actions and needs more computation.

Nowadays, however, one of the main challenges of the motion planning algorithms is their rule-based approach, defined to work in an "if-then" manner, which can induce undesired

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vehicle behaviours in complex or unknown scenarios. For example, when an AV is trying to enter a highway, if enough distance gap between the vehicles is not found, the vehicle can remain stopped in the acceleration lane, because it has not found an appropriate gap and it has been programmed to stop safely until it finds one. These kinds of situations, of course, make CAVs unattractive for users and could also have negative impacts on traffic efficiency, let alone road safety. Even though researchers are working on optimisation, there is a point where improvements are hard to achieve, since the degrees of freedom are limited.

To overcome this, scenario independency could bring very positive results. To this extent new risk field driving approaches are emerging (Wang et al., 2016). Their basic functioning consists of defining risk fields (Figure 7) for each one of the road participants, objects, and infrastructure, so the vehicle can drive through the local minimums, i.e., “avoiding” risks. This would provide the vehicle with great flexibility and adaptability to the environment and would make CAVs independent from the scenario. However, to define the risk fields accurately, the ego vehicle needs to be able to compute them, based on its perception and scene representation systems, and, desirably, enriched by connectivity. This would require CAVs to be equipped with powerful computational systems and vehicles to communicate the necessary data (e.g., mass, speed, acceleration) between so they can generate accurate risk fields.

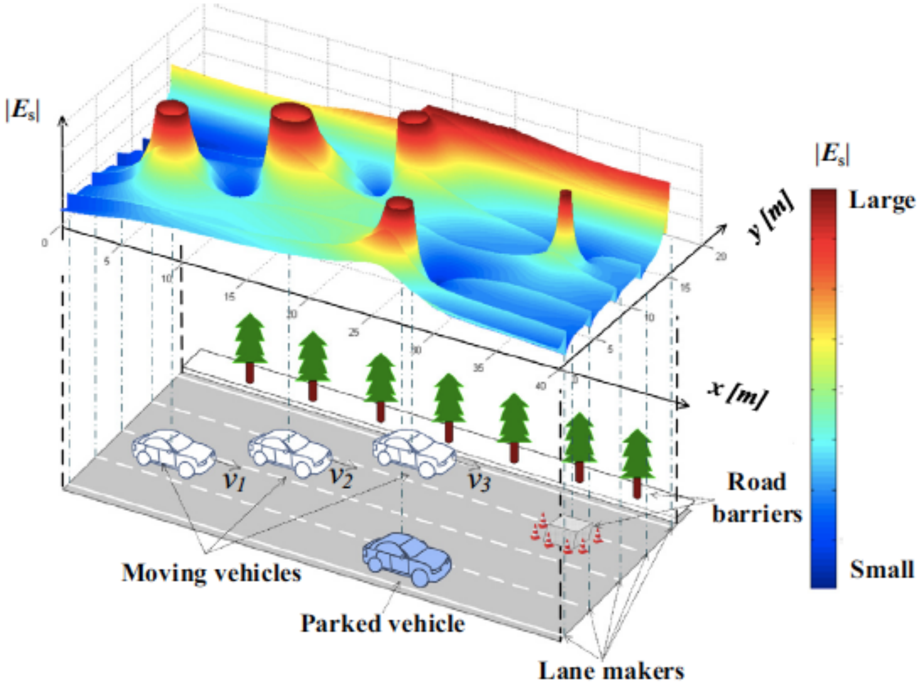

Figure 7: Multi-vehicle scenario with the different driving safety fields (Source: (Wang et al., 2016))

Connectivity

Vehicle connectivity is a key element for an effective delivery of the economic and societal benefits of CAVs. In the long-term it will enable new data services, driving efficiency, road safety, and a new understanding of mobility patterns. Connectivity includes communication

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of the ego vehicle with the infrastructure (V2I), other vehicles (V2V) and other road elements or users in general (V2X), like VRUs.

In relation to safety, it is important to understand how important and necessary connectivity is. Since current AV designs do not require V2V or V2I, this can lead to a lack of information that can make certain kinds of crashes persist. A recent study from the UC Berkeley (Shetty et al., 2021) shows that fully autonomous vehicles cannot guarantee safety in the absence of connectivity, suggesting that incorporating it is an essential step to make CAVs safe. In addition, V2I and V2V could complement the vehicle's perception system when the limit of the ODD is reached. Think for example about a scenario where infrastructure provides information to the vehicle about a pedestrian crossing that has not been possible to detect by the vehicle's own perception system due to adverse weather conditions, like dense fog or rain. A similar approach is being studied and tested in SAFE-UP's Demo 4.

However, such levels of connectivity bring their own safety challenges. Relying on information from other vehicles or infrastructure makes the ego vehicle vulnerable to wrong communications or security attacks. This makes it crucial to ensure communication standards and high-bandwidth low-latency communications. Additionally, equipping the roads with sensors and requiring all vehicles to communicate with one another would require a significant amount of time, agreements, and economic resources.

Also, connectivity would allow for a better traffic efficiency. It is predicted that if all vehicles have collision avoidance systems and V2V communication, highway capacity could be increased by 273% (Tientrakool et al., 2011).

On the other hand, CAVs represent a whole new paradigm when it comes to generated data. Research suggests connected and automated vehicles could generate more than 4TB of data per day (5GAA, 2017). These new data streams could be consumed by digital twins to allow new traffic management strategies, improved road information, or better identification of travel patterns, bringing journey experience to a new level for users. However, this would require CAVs to be equipped with powerful computation systems and storage capacity, imposing more constraints to space, heat dissipation, and the cost of executing the heuristic calculations or artificial intelligence needed to drive autonomously.

To overcome the issues with increase storage capacity and computation, an important part of the workload is being translated to the cloud. However, again this demands strict requirements in terms of latency, network availability, and reliability given the critical nature of CAVs and their safety-critical operations.

Ergonomics and design

As has been mentioned in 2.2, the interaction between the driver and the vehicle will change depending on the automation level of the vehicle, going through a phase where the driving task will be shared between the human driver and the vehicle. Bellet et al. (2019) proposed a definition of the human-machine transition system, which can be observed in Figure 8.

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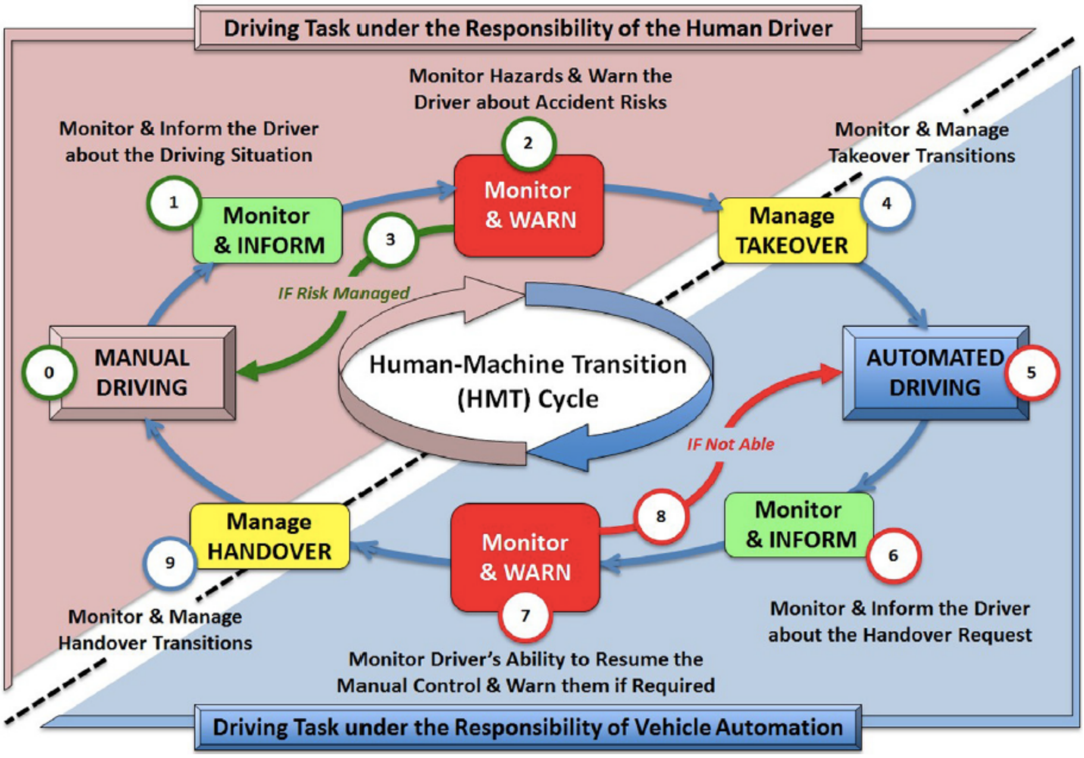

Figure 8: Human-Machine transition cycle (Source: (Bellet et al., 2019))

In the case of manual driving (SAE L0 to L2) as the initial state, the driving task is the responsibility of the human driver, and the vehicle supports him/her by assessing the traffic situation and its risks, to accordingly activate the appropriate HMI system to assist the driver (information, warning, or takeover).

In the case of automated driving (SAE L3 to L5), the driving task is the responsibility of the vehicle. The vehicle needs to constantly monitor the systems' limits or potential failures to assess the need of a transfer to the human driver, first generating a Take-Over Request and then managing the handover transition (Bellet et al., 2019).

To guarantee a smooth and safe transfer of functions, it is very important to understand and design the interaction between the driver and vehicle, and to account for the consequences it could have. As described in the BRAVE[2] project, a successful Human-machine interface (HMI) needs to be unobtrusive and satisfactory, intuitive to use, and of course, safe.

In this regard, several challenges had been identified, like how to ensure driver is in the loop for L2 vehicles and below. Or for L3 and higher levels, how to ensure the driver is able to transfer back into the driving task without startling effects and low situational awareness (Rosenqvist, 2019).

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[2] http://www.brave-project.eu/

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3.2 Key priorities and challenges

Robust and affordable perception systems

Current perception systems are quite capable of getting a correct representation of the vehicle's environment, enabled by effective and redundant "sensor-fusion" systems able to compensate for the weaknesses of each kind of sensor. However, they are not yet able to cope with the whole range of driving scenarios, specially being affected by expanded ODDs including adverse weather conditions (Coppola & Bergen, 2021) or more aggressive driving styles, like higher speeds or closer gaps (Proff et al., 2019). Until these details are solved, widespread commercialisation will be hard.

Several projects are already working on this at the European level. The RobustSENSE[3] project is focused on introducing reliable, secure, and trustable sensors and software by implementing self-diagnosis, adaptation and robustness, developing metrics to measure sensor system reliability on every level of assistance and automation systems. Also, the DENSE[4] project investigated how to deal with the variety of environmental conditions, with the objective to develop and validate an all-weather sensor-suite for traffic services, driver assistance and automated driving. SAFE-UP is not ignoring these challenges, and Demo 2 is working on the quantification of bad weather effects on perception systems, and how they can be improved.

In addition, new hardware concepts for sensors and computing units are vital to reach the computing power needed to appropriately perceive complex driving scenarios while keeping affordable energy consumption and integration costs.

Finally, new and improved AI and ML algorithms are needed to correctly identify and classify road elements. This comes, however, with an increased complexity of systems that poses new challenges to vehicle safety and validation, since these algorithms are often considered like a "black-box", being this a problem for correct system interpretation and predictability. In addition, there will be an increased need to handle remote software updates and increased maintenance or aftermarket requirements.

Adaptative and efficient driving systems

In order to ensure a proper introduction of AVs and avoid unintended or misunderstood use that has already caused some accidents, it is important to define vehicle capabilities for each one of the designated Operational Design Domains (ODDs). So far, OEMs and designers of AVs have only published ODDs for passenger cars in their own safety reports (Waymo 2017, General Motors 2018, Ford 2018). More recently, Mercedes (2019) also made available first descriptions of ODDs for motorway. However, for a considerable number of cases, this is not

[3] https://www.robustsense.eu/
[4] https://www.dense247.eu/

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often specified, and assumptions need to be made, leaving users and regulators confused. For this reason, it is crucial to have a harmonised definition of the ODDs, their functionalities and their limits (Rosenqvist, 2019).

Some organisations, like the Association for Standardization of Automation and Measuring Systems (ASAM[5]) have already started working on this area. More specifically, they are working on a standard called "OpenODD", with the first version planned to be released in March 2022 (Romainczyk & Wenzel, 2021). However, even though OEMs will still be required to provide the ODD for each vehicle, standardisation will positively contribute into having common definitions of ODDs, making it easier for certification bodies and user when it comes to understanding the limits of the vehicle and the consequent human driver responsibilities.

In addition, there is also the need to develop technologies supporting vehicle's own understanding of ODDs, followed by a "fail operational" system, which in the case that the limit of the ODD is reached, the vehicle brings itself into a safe state within a minimum risk manoeuvre. Hence, vehicles must be provided with comprehensive fault detection, identification and accommodation capabilities so that malfunctions can be immediately diagnosed and enable safe switching.

On the other hand, as mentioned, scenario independency is an important milestone to be achieved if we want to ensure higher flexibility and adaptability of AVs. Small disturbances like construction works, left turns, objects, and pedestrians remain headaches for computer drivers (Coppola & Bergen, 2021). This flexibility can be crucial to ensure high traffic efficiency standards whilst guaranteeing safety in new and expanded ODDs.

<u>Standardised connectivity requirements and planning for deployment</u>

As has been stated, connectivity could be key to ensure the long-awaited and promised final success of the future traffic management strategies, and, more importantly, to guarantee that AVs operate safely, by supporting their perception systems in order to prevent accidents and crashes. However, an exhaustive and rigorous quantification of the vehicle connectivity needs has not been performed to date. More specifically, the V2V, V2I, and more in general V2X requirements to provide the expected benefits of CAVs, have not been clearly quantified, defined, and further standardised. There is a strong need from the OEMs, infrastructure managers and regulators to know which connectivity systems are crucial to ensure safe and resilient autonomous driving.

To this end, following a standardisation and harmonisation of the ODDs, it is important to define the role of connectivity for CAVs. The good news is that connectivity is one of the areas that is seeing the higher numbers of standards being published in the last years, as shown in the ARCADE website (Figure 9). It needs to be said that this is completely expected, because

[5] https://www.asam.net/

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no communication can happen without a standardisation of bandwidths, interfaces, frequencies, protocols, etc.

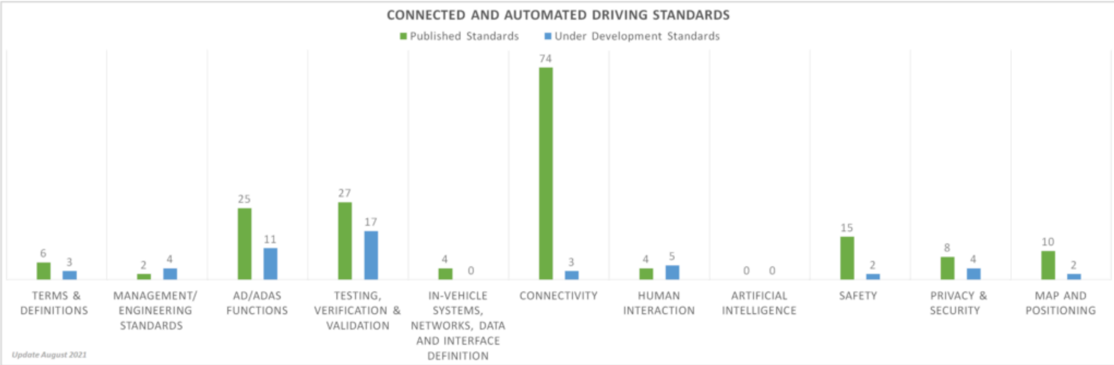

Figure 9: Connected and automated driving standards divided by domains (Source: ARCADE)

When this role has been defined, there will also be a need to ensure that different OEMs' vehicles communicate with each other, if necessary, to allow V2V bring the benefits it is promising, once they have been confirmed through successful R&I initiatives. Currently this is not happening and could hinder the potential benefits of CAVs in the future.

In addition, even though the connectivity requirements are known, or at least better defined, the time horizon cannot be forgotten, in the sense that the full deployment of V2I will be costly, time-consuming and resource consuming. To this extent, taking into account implementation times and costs, it is important to prioritise where to deploy the first use cases and when. Strategical planning is needed, aligned with the deployment of other technologies like 5G and C-ITS, which will be very important to cater for the impacts brought by connectivity.

Finally, when the connectivity requirements are established, it will facilitate the work of regulators when it comes to defining responsibility and liability of accidents in certain safety-critical scenarios. This, in turn, imposes more responsibility to infrastructure managers, as they will need to ensure proper maintenance standards and inspections in order to ensure that proper communication happens. Additional to this, (cyber)secure and safe communications respecting privacy and various levels of trust need to be standardised and established.

<u>Ensure safe and seamless interaction between vehicle and driver</u>

Even though the introduction of advanced driving systems contributes to increase road safety, new types of risk also emerge, since the risk balance of the driving task between the driver and the vehicle is modified. The transfer of the driving task from the vehicle to the human poses the challenge of the assessment of the human driver capabilities to manually perform the current driving task. In addition, the driver must be clearly informed by the AV about the element of the driving task that is being carried out by the vehicle and, if required, about the incoming situations and the possibility to resume manual control.

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3.3 The way forward

When facing the challenges of increasing vehicle's ability to perceive the environment, drive efficiently and ensuring safety, the major items that could imply an important breakthrough towards driving automation are:

Table 2: Major identified breakthroughs for vehicle technology

Code	Category	Breakthrough
VT1	Sensors	Sensor suite robustness to expanded ODDs (all weather conditions, range of speeds, types of roads, etc.)
VT2	Sensors	Affordable perception system costs while ensuring reliability and safety
VT3	Automated driving systems	Scenario independency for a more efficient and safe driving
VT4	Automated driving systems	Harmonisation and catalogue of ODDs, how does the vehicle understand them, and fail-operational architectures
VT5	Connectivity	Definition and standardisation of connectivity requirements for each ODD
VT6	Connectivity	(Cyber)secure and safe communications respecting privacy and trust
VT7	Connectivity	Definition of agreements and trust levels of OEMs between other OEMs, infrastructure, and other road users (VRUs)
VT8	Computation	Improved computation and storage systems
VT9	HMI	Seamless control transfer between vehicle and driver

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4. Infrastructure

4.1 Where are we today?

Road infrastructure is already equipped with numerous sensors to gather information on traffic and the environment. A good categorisation of infrastructure readiness levels is provided by the Infrastructure Support Levels for Automated Driving (ISAD) classification developed in INFRAMIX project (Carreras et al., 2018), as described in **Error! Reference source not found.**.

	Level	Name	Description	Digital information provided to AVs			
				Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Digital infrastructure	A	Cooperative driving	Based on the real-time information on vehicles movements, he infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow	X	X	X	X
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time	X	X	X	
	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs	X	X		
Conventional infrastructure	D	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs	X			
	E	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs				

Figure 10: Infrastructure Support Levels for Automated Driving (ISAD) categories (Source: H2020 INFRAMIX project based on Carreras et al. (2018))

Following ISAD classification, roads without any support for automation rank at the lowest level (Level E), moving up levels as they digitally map static or dynamic information (Levels D and C, respectively), can perceive traffic situation through sensors and communication with vehicles (Level B), up to the point of being able to offer them recommendations from a traffic management perspective (Level A).

It is a safe assumption that reaching high ISAD levels for the highway and primary road network seems feasible, as major corridors in EU regions are already in Level B (or at least close to it), even if investments are still required to homogenise readiness levels across it. On the contrary, it looks like extending such readiness levels to secondary roads might be largely unfeasible, needing to upgrade a vast extension from the lowest readiness levels while facing budget limitations (Martínez-Díaz et al., 2019). Level A infrastructure extends the operational domains of CAVs, offering the highest advantages in terms of travel experience, traffic efficiency and safety. Yet, if consumers want to be able to travel everywhere, CAVs would need to be able to operate in infrastructures with no support for them (Level E), solely relying in their sensors specially where road characteristics are less favourable for their environment and infrastructure perception capabilities.

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4.2 Key priorities and challenges

Physical infrastructure

CAVs ability to make sense of the surrounding environment crucially depends on the range and capabilities of onboard sensors. Image recognition technology requires that all information inputs are sufficiently visible (for example: road edges, curves, speed limits and other signages) to locate, recognise and proceed with specific actions (manoeuvres).

Avoiding sharp changes in road layout curvatures and slopes will greatly facilitate the vehicle capacity to read the environment in real time.

Additionally, consistent lane width and hard shoulders (safe harbour) will make it easier to respond in case of malfunction and be more forgiving with potential mistakes of fallible CAVs technology (Irving, 2019).

Signs and markings need to be correctly located and maintained for optimal readability, however, neither its design or maintenance is standard across countries (sometimes not even across regions). It is likely that the deployment of CAVs will impose the need for global standardisation of road signage and markings, while also requiring a raise in maintenance standards (with greater expenses in correcting faded road markings or excessive roadside vegetation) and its monitoring (Liu et al., 2019).

Temporary signs also pose a hard challenge to tackle, as there is a broad range of situations that CAVs will need to interpret in different contexts. It is important that all the changes in road layout are correctly communicated to CAVs, and imaging perception might be required for the temporal situations that might disrupt the road layout for a certain amount of time.

Moreover, some implications for pavement and drainage are also envisioned. CAVs Lane-Keeping-Systems might make them run more systematically over certain parts of the pavement than human drivers do, so reinforcement might be needed along tracks. Drainage systems design and maintenance might be stricter to avoid CAVs systems freezing due to an excessive accumulation of water.

Digital infrastructure

Road infrastructure can support and guide automated vehicles by extending their environment-sensing capabilities and sharing useful information extracted from the already numerous sensors deployed (loop detectors, cameras, radars, etc). CAVs will benefit from this support, releasing pressure on their sensing capabilities to achieve certain performance. Additionally, V2X communication can in turn benefit infrastructure management with enhanced information coming from on-road vehicles acting as distributed sensors. Such information can be treated in traffic management centres that then fed back into cars to nudge

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their decision making towards smoother traffic and prevention of risky situations, allowing them to better react to accidents and emergencies (Liu et al., 2019).

However, to reach these outcomes, roads need to be retrofitted with enhanced communication technology. A reliable and powerful V2I adapted infrastructure is mandatory in making CAD possible, via a secure wireless communication system. Physically this will require a set of antennas (DSRC or ITS-G5) to ensure the right coverage, even cheaper for both infrastructure providers and OEMs would be to rely on mobile communication networks (4G/5G), which could also support additional services like entertainment streaming services. Experts still favour the reliability of DSRC or ITS-G5, as 5G is neither expected to meet the V2X requirements nor be deployed with enough territorial coverage soon ((Martínez-Díaz et al., 2019); (Verbenkov, 2021)). A hybrid communication system including several technologies will offer a cost-efficient solution ensuring the right coverage in different parts of the infrastructure depending on layout complexity and the expected volume of interactions is likely to be the most advisable option.

The non-avoidable part would be to mount digital single communication beacons on traffic signs. Potentially, equipping junctions with optic fiber will make room more easily for future adaptations, as this is where the highest density of signs and information is produced in the road network. In any case, besides these investment costs, some savings might arise to due to a reduced need for speed limit enforcement (radars) as CAVs are programmed to obey the rules.

This will allow a proper V2I communication essential for enhanced traffic management, where AVs can act as decentralised sensors for infrastructure's local and global surveillance system. Processing this information in a traffic centre that selects the best network-wide strategy and feeds it back to CAVs, allowing the suggestion of specific actions even to just a particular group (like optimal speeds, gaps between vehicles and routes). This cooperative V2I communications will be conducted by physical local stations (management centres) covering certain regions, coordinating the information interchange in their area of influence, and passing it on to nearby stations for a system-wide management (Martínez-Díaz et al., 2019). Such nodes will process and simplify the information forwarded to CAVs potentially allowing them to reduce their data storage and computational requirements[6].

In any case, the benefits of smoother traffic resulting from the combination of such capabilities will depend on how much CAVs decision-making is cooperative or individualistic, based also in how V2V communications are defined. Researchers claim that freeway capacity will progressively be reduced with penetration rates of CAVs under individualistic decision frameworks. On the contrary, under cooperative decision-making a 10% rate of AVs is assumed to lead to around 30-40% reduction in total travel time compared with same travel demand without CAVs.

[6] A major barrier for these outcomes to be achieved is the need of CAVs manufacturers to rely on external data, making it hard to accept when the liability in case of accident is not shared.

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An intrinsic threat to any V2V or V2I communication is its potential vulnerability to malicious hacking, cyber-attack, or physical infrastructure sabotage. The use of malware, attacks to the management centre or the deliberate alteration of communication beacons (among others) can potentially disrupt the correct functioning of many cars affecting the whole transport network performance. CAV deployment will require the development of communication standards ensuring interoperability, ensuring redundancy on the digital infrastructure, and changes in legislation that take these issues into account[7].

<u>Increased pressure on urban space</u>

More on the urban side of the issue, McKinsey (2019) points out that it is important to redefine how curb side parking is allocated to promote the shared use of AVs. Daytime parking can be easily shifted to cities' periphery (Zakharenko, 2016) while lower transportation costs will give incentives for further sprawl. Likely, a dedicated parking belt arises outside the commuting zone, gathering most AVs for daytime parking, where land is cheaper. We believe this might be avoided by exploiting the complementarity between commuters and residents parking, suggesting the need to rethink off-street parking too (McKinsey, 2019). Shared space and virtual garage operators can offer at least partial solutions to this issue. Zakharenko (2016) also predicts traffic increase as a result of the previous effects, yet congestion worsening will depend on how much more efficiently AVs can make use of available road capacity.

In any case, this empty travel generates a new regulatory problem. If congestion is to be avoided the regulator will not only need to face inbound traffic but also the cruising and returning one too. The right balance between increased empty miles travelled and parking pressure will be a challenge to solve.

Additionally, how AVs are used to access the city will depend on the comparative variable cost between transit options and AVs. Under the right circumstances, AVs can serve as feeders to the mass transit system covering the part where it is not a competitive alternative. Under not so favourable ones, AVs will take most of the trips putting big pressure on available road and parking capacity.

[7] See (Douma & Palodichuk, 2012) for a legal discussion of CAVs related issues.

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4.3 The way forward

When facing the challenge to increase infrastructure's CAVs-readiness, the first things developers and public authorities should focus are described in the table below.

Table 3: Major identified breakthroughs for infrastructure

Code	Category	Breakthrough
I1	Physical infrastructure	Increased maintenance standards, ensuring that CAVs ability to drive is not impaired by infrastructure deficiencies
I2	Physical Infrastructure	Improved and robust infrastructure safety measures to mitigate potential for AV malfunctioning
I3	Digital infrastructure	Defined and standardised interactions between digital infrastructure and CAVs
I4	Deployment	Validated communication framework while investigating the benefits of common infrastructure classifications (i.e. ISAD)
I5	Deployment	Defined financing models to establish the role public (road) authorities should take
I6	Traffic management	Defined Traffic management strategies

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5. Regulations

This pillar covers the role of regulations in the overall introduction and adoption of CAVs. Regulations, legislation, and standards are often identified as “enablers” or “blockers” for the introduction of self-driving (McKinsey, 2016). The influence of such norms reaches to all the phases, including development, testing and deployment (Zenzic, 2020).

In relation to development, for example, the approach to regulation adopted by the German authorities, allowing up to level 3 automation, had a positive impact by providing clarity and security for investments to the national car industry (Altunyaldiz, 2020).

On the other hand, cities, regions, and countries allowing the testing of AVs in open roads are necessary to identify the vehicle and infrastructure needs, as well as the benefits and the hurdles that automation brings to society. Allowing this, will also incentivise piloting activities, with a clear definition of the features that can be tested, in which areas, and which interactions are allowed with other road users and/or infrastructure.

Finally, piloting and testing are very important to foster user acceptance of CAVs, as explained in 6.2, so it is key that regulations allow them. In addition, if regulations certify that a certain autonomous vehicle is safe, it will create a positive feeling for the user by reassuring the credibility of the technology, a decisive factor for user acceptance and adoption in society (CCAM, 2021).

5.1 Where are we today?

To have a clear picture of the European regulatory framework, we will provide an explanation of the main working groups dealing with vehicle type approval, with special focus to those related to automated driving, based on the overview presented in Elpuente et al. (2021).

<u>UNECE and the World Forum for Harmonisation of Vehicle Regulations (WP.29)</u>

At an international level, the World Forum for Harmonisation of Vehicle Regulations – WP.29 – (a subsidiary body of the Inland Transport Committee of the UNECE, see Figure 11 below), is the most important group. The main objective is to work on the incorporation into the regulatory framework of the technological innovations of vehicles, in order to make vehicles safer and more environmentally sustainable.

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Figure 11: UNECE structure (Source: (Elpuente et al., 2021))

Until June 2018, the WP.29 had six permanent Working Parties, also known as GRs (Groupe Rapporteur): Noise (GRB), Lighting and Light-Signalling (GRE), Pollution and Energy (GRPE), Brakes and Running Gear (GRRF), General Safety Provisions (GRSG) and Passive Safety (GRSP). Moreover, there were some Informal working groups focused in other related topics. However, in June 2018 a new dedicated GR working group was announced, called the Working Group on Automated Driving (GRVA). The focus of this group was to address all topics related to automated driving, which were previously managed in the "Informal Group on Intelligent Transport Systems/Automated Driving (ITS/AD)". Moving the discussions on automated vehicles from an informal group to a dedicated GR has been a big step, suggesting that the AV revolution is now a fact that needs to be considered in order to cater all the benefits it promises to deliver.

Global Forum for Road Traffic Safety (WP.1)

Within the scope of UNECE, there is also a Working Party dealing with road traffic safety. This WP is the one behind the Convention of Road Traffic of 1968 (also known as Vienna Convention). In this convention, it was established that the driver must be always in control of the vehicle, something that hindered the development and introduction of autonomous driving features. However, in March 2016, an amendment of the Vienna Convention modified these articles, making it compatible with autonomous driving. In addition, there has been an agreement between WP.1 and WP.29 of the UNECE to keep working together in the future.

European Union

The European Union, through its different bodies, is responsible for the definition of a Whole Vehicle Type Approval system, within Europe. This system is based on the mandatory universal recognition of the approvals issued by any Approval Authority by all the Member States. The two main tools created by the EU for the purpose of vehicle type approval are:

Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018. This regulation repeals Directive 2007/46/EC and defines the administrative procedures as well as the technical requirements of passenger and goods motor vehicles. Even though it uses a similar approach for the type approval to the procedure established in the Directive

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2007/46/EC, it defines a higher level of responsibility for the different stakeholders of the type approval process.

Regulation (EU) 2019/2144 of the European Parliament and of the Council of 27 November 2019. It defines type approval requirements for motor vehicles and their trailers, and systems, components and separate technical units intended for such vehicles. In regard to their general safety and the protection of vehicle occupants and VRUs it defines a roadmap for the upcoming years in mandatory safety features to be included in motor vehicles and their trailers. It also opens the door for new regulations covering new technologies.

All in all, the homologation process based on the UNECE regulatory framework has been a single step at the end of the development phase. The manufacturer can sell its vehicles once the proper documentation has been generated after having conducted several tests to determine if the system met the required safety levels or not. In the classic homologation process (V-model), the concept of failsafe operation has been always considered. When the systems were highly standardised, some components were considered likely to break/malfunction. This analysis led to the selection of the component that could result in a critical failure, and since there was a strong statistical sample (due to extensive generalization in the market), the failure could be determined through accidentology (Elpuente et al., 2021).

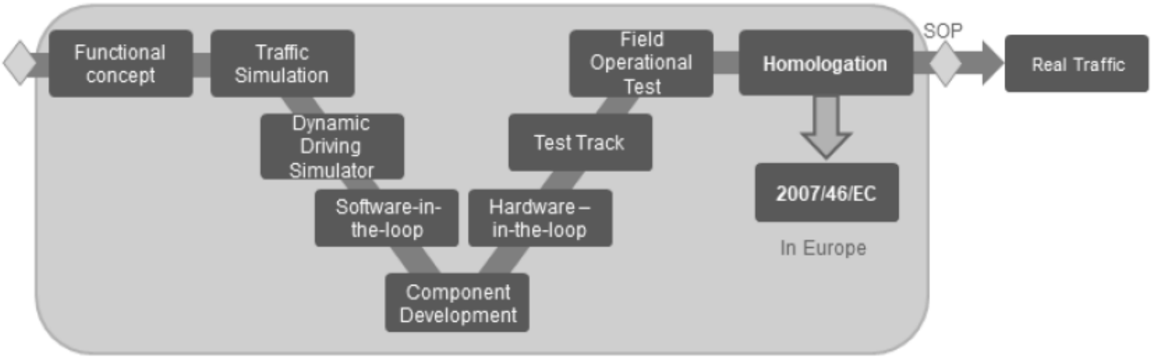

Figure 12: Classic V-model approach for developing process

5.2 Key priorities and challenges

Future vehicle type approval

With the recent introduction of the new Driver Assistance Systems in the EU market, the risk evaluation in fail condition turned out to be quite hard to perform. Fundamental differences in architecture and in intended functionalities make generic procedure complicated to define. In addition, with the vehicle taking over some driving responsibilities that were previously left on the user side, evaluating how safe a vehicle is not only means that it is able to accelerate, brake, or steer in a certain way, for example, but also that it is able to properly perceive the environment and to take appropriate decisions considering other road users, traffic rules, and other constraints. Consequently, new regulations should steer away from the classical approach (V-model) to a case by case evaluation (Elpuente et al., 2021).

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To this end, higher levels of automation require scenario-based validation methodologies. To enable this new approach, it is important to standardise and harmonise the definition of ODDs (Rosenqvist, 2019) to define the expected functionality of the vehicle in each scenario (i.e. type of road, traffic situation, weather, speeds, etc.). Once this is achieved, it will contribute to the harmonisation of testing, validation and certification methodologies, a topic addressed by the HEADSTART[8] project.

In line with the previous paragraph, it is key to identify and collect all relevant critical scenarios and their probability of occurrence, something to which SAFE-UP is actively contributing. In fact, the SRIA of the European CCAM Partnership raised the need forf the establishment of an "EU wide database of relevant scenarios for validation" to derive test cases as a validation of CAVs, in future type approval schemes and in consumer testing campaigns (CCAM, 2021). This will introduce more pressure on the validation process, which will need to follow hybrid approaches with physical and virtual testing, in order to reduce the high number of test-kilometers needed to validate a vehicle.

It is also important not to leave out of the validation system the updates of functions during the vehicle lifecycle as well as self-learning capabilities of AVs (i.e. because of AI algorithms). For this, procedures to manage validation of these updates need to be developed as well.

Human factors are also important to validate CAVs. Connected to what has been said in previous sections, human-vehicle interaction is crucial to assure CAVs' road safety. The same SRIA document from the CCAM Partnership addressed the need for harmonised HMI designs and testing. Closely related, an understanding of human driving performance will contribute to defining a reference for the AVs system's performance in reducing the number of crashes and fatalities. As stated by the CCAM Partnership, "such a reference model of the performance spectrum of human drivers will allow a direct comparison to an automated driving system in the simulation of a specific situation and thus support the deployment of the results" (CCAM, 2021) from the future type approval tools and methodologies.

Therefore, we must not only ensure that automated vehicles are safe, but that they are also perceived as driving safely by other road participants, without creating unexpected accidents or new safety-critical situations. Nevertheless, research shows that such consensus of what is meant by "driving safely" does not exist yet (Tejada et al., 2020). Once this "catalogue" of safe driving is defined, it will contribute positively to safety assessment of AVs, by observing how the vehicle adheres to it and what are the effects of not doing so.

Harmonisation

Some authors (de Cruz, 1999; Kamba, 1974) state that harmonisation looks to "effect an approximation or coordination of different legal provision or systems by eliminating major

[8] https://www.headstart-project.eu/

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differences and creating minimum requirements or standards". This is an important step for the introduction of AVs, affecting all the pillars.

From the vehicle technology point of view. The harmonisation of ODDs and perception requirements will set the basis of how vehicles are expected to perform in various situations, and this in turn will facilitate the type approval of the vehicles. The same applies for the connectivity requirements. Different methods have been used for AV validation and homologation, but to date, no common standard methodologies exist that meet all the testing requirements, validation and certification of all levels and use cases of automated driving (CCAM, 2021). In this direction, the L3Pilot[9] European project developed a sharing framework for aggregated test data and a common data format for EU wide application.

In addition, there's a need to harmonise HMI designs and testing to enable a more effective and faster user acceptance of autonomous vehicles while ensuring driver's safety.

Moreover, if the perception, decision, and connectivity requirements are harmonised to guarantee safety via vehicle approval, it will have a two-side effect. On the one hand, it will create confidence among users regarding CAV's safety, which will encourage adoption and acceptance. On the other hand, it will create a clear path for automakers, which could increase the stability of the market and encourage future investments.

From the infrastructure point of view, there is also a need to harmonise the traffic rules and their interpretation. The variation of traffic rules between cities, regions and countries creates complexity and contributes negatively to vehicle's environment perception, which requires it to have more knowledge, hindering a widespread uptake.

Privacy, Data protection, and cyber-security

The human driver monitoring status to supervise and evaluate its ability to get transferred the driving task by the HMI poses some challenges related to privacy. The data generated by these systems could be used by insurance companies to support *Pay As You Drive* (PAYD) approaches or to settle liability claims. PAYD would use variable insurance pricing depending on the driver's performance (Ferenzy et al., 2016), having strong effects on driving safety and fair pricing, both negative and positive. It is unclear whether these privacy concerns can be fully accommodated by the existing regulations (such as GDPR) or technical solutions, like unwanted data access or anonymization.

In fact, in 2020, a report from a European Commission Expert Group (DG Research and Innovation, 2020) established 20 recommendations for CAVs, including safeguarding information privacy and informed consent, developing transparency strategies to inform users and pedestrians about data collection, and identifying and protecting CAV relevant high-value datasets as public and open infrastructural resources.

[9] https://l3pilot.eu/

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Additionally, this extending the system domains beyond the vehicle through connectivity and the amounts of generated data, might be exploited to for threats and open a new door for hackers and cyber attackers. In this regard, it is crucial that cyber security and resilience are guaranteed in order to add value across the economy and boost consumer confidence (Zenzic, 2020). There are arguably no other topics in this roadmap as pervasive as cyber resilience since it cuts across all the different pillars and breakthroughs.

To this extent, it is important that early investments from government and industry ensures safe and trusted services. The CCAM Partnership is already addressing the cybersecurity issue under its "*Cluster 5: Key Enabling Technologies"*, with the aim to contribute to a better performance of vehicle-transport system integration. Also, the GRVA from the WP.29 from UNECE, released in 2020 a report proposing interpretation documents for UN Regulation No. 155 (Cyber security and cyber security management system) (GRVA, 2021). However, the path has just started, and regulations ensuring cyber resilient systems will need to continue developing as connectivity in CAVs keeps expanding from small pilots to the whole transport system.

Responsibility and liability

As mentioned before, the introduction of automated driving technologies contributes to increased road safety, but also shifts the risk balance between the driver and the vehicle. Bellet et al. (2019) suggests that vehicle designers cannot omit the legal implications of HMI when developing and implementing them, but that on the other hand, providing a legal "answer" to the designers is only necessary for problems which are effectively "asked" or created by HMI systems. As a consequence, it is necessary to support the development of such systems by a common framework considering HMI and legal aspects.

The cycle presented in Figure 8 could inspire legal specialists and ethicists to interrogate issues around the human-vehicle interaction implicit in autonomous vehicles. For example, when the vehicle is doing the driving task, in the case of a system failure, is the driver entitled for compensation for own injury or property losses? Who is to be held responsible for violating traffic laws? Can the driver be continuously excluded from the driving task?

Or in the case of the assessment of the driver's capabilities to take back control in L3 vehicles, it is difficult (biologically and cognitively) and ethically questionable to charge the human with the full responsibility for resuming the driving task in all situations, at the same time that an AD environment is created which excludes them from the loop of control. Consequently, technical solutions in the case the human driver is unavailable should be mandatory (and not optional, as suggested by L3 SAE definition) and new liability legislations should be redefined accordingly for L3.

These changes in the risk balance induced by sharing the driving task between the human driver and the vehicle also create new challenges for insurance companies.

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In addition, proper and standardised rules to handle vehicle updates (i.e. software updates) need to be established in order to derive liability in case of accidents or undesired scenarios. For example, concerns have appeared around blaming the vehicle for some accident when the owner has not installed the last (and requested) software updates. This also comes to the fore with the new vehicle type approval process, which will need to take into account these Over-the-Air (OTA) updates.

For this reason, and the one mentioned in the driving task handover, it is important to train users about what are their responsibilities and how they should interact with AVs. Consequently, a driver training revision is needed to accommodate the expansion of CAVs. Finally, the definition and standardisation of vehicle's connectivity requirements for the different ODDs will also contribute to devise who could be liable in the case of a failure, either from the vehicle's side, the infrastructure side, or any other road user.

5.3 The way forward

Regarding regulations, the main challenges and milestones researchers, policy makers and regulators should focus on to enable an efficient, safe, trusted, and fast introduction of CAVs are presented in the table below.

Table 4: Major identified breakthroughs for regulations

Code	Category	Breakthrough
R1	Type approval	Create a common type approval at EU level based on CAVs' needs, updating current procedures. Defined ODD catalogue.
R2	Type approval	New validation methodologies (simulation and virtual testing) included in safety assessments to reduce time and costs (required test kilometres)
R3	Type approval	Methodology for testing new software systems, including AI and ML
R4	Demonstration	Rules of road established for shared spaces in urban areas
R5	Data protection	Clear data sharing environment definition (what data is collected, how it is collected, how is it stored, who is the owner, etc.)

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R6	Cybersecurity	Standardised approach of failsafe operation systems in case of cyber attack
R7	Cybersecurity	Developed Cyber security regulations
R8	Harmonisation	Harmonise traffic rules and infrastructure requirements (physical & digital) at EU level
R9	Responsibility and liability	Clear legal framework established (including the ODD, fault analysis, and human interaction) to determine who is responsible for each situation
R10	Responsibility and liability	New driver training permits including the interaction with different SAE levels and ODDs

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6. User approach

6.1 Where are we today?

The importance of a user-centric strategy

To fully leverage the intended safety, traffic flow and urban decongestion effects of AVs, it is important for users to fully embrace the technology. Also, increased uptake of AVs creates urgency for well-suited regulation, infrastructure and next-generation vehicle technologies. Thus, creating user acceptance is crucial to achieve a substantial uptake of AV among potential users. The road to achieving user acceptance brings interesting synergies with design processes of the different pillars. A user-centred design process calls for elicitation of user needs through demonstrations. Especially the Human-Machine Interface (HMI) of AVs could benefit from proactively seeking user feedback in design phases (European Comission, 2019a). The final key development in the AV user approach is driver training. Instructing future AV users on AV usage is key to build trust and ensure AV safety benefits ((Markvica et al., 2020); (Merriman et al., 2021)). This chapter presents current challenges related to AV users, alongside challenges and a vision for next steps.

Knowledge on users

In general, people are still concerned with AV technology. The aggregated user acceptance level of road AVs depends on the level of automation, however, it does not exceed 30%, with 3 out of 5 SAE levels below 20% (Markvica et al., 2020). In general, the same factors apply to the user acceptance of shared as well as private AVs, albeit to a different weighting due to their design differences. For example, the perceived usefulness is more important to people when opting for a personally owned AV, compared to using a shared AV concept. Unsurprisingly, factors like trust, ease-of-use, perceived safety & usefulness are significant to users' behavioural intention to accept or use AVs ((Nordhoff et al., 2019); (Kaye et al., 2021); (Motamendi et al., 2019)). However, this information is relevant to bring strategic focus to the user approach.

Several safety & risk concerns have emerged from research regarding the general user acceptance of AV. However, according to Motamendi (2019), the perceived usefulness and safety of an AV are the most important factors.

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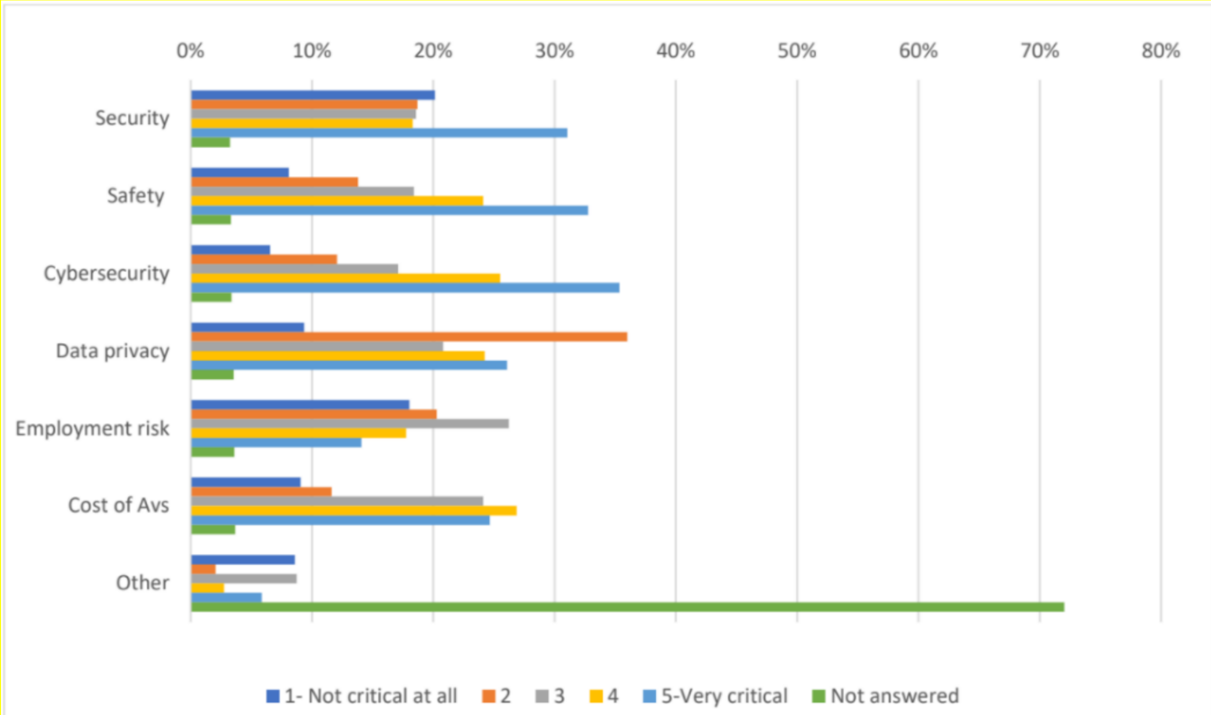

Figure 13: User concerns regarding road AV (Source: Markvica et al., 2020)

Figure 13 shows a list of concerns people have in general on road AVs, provided by a survey under the Drive2theFuture[10] project. Safety & security concerns equipment and system failure or system performance in poor weather/terrain or unexpected conditions. Cyber security relates to the fear of terrorism and hacking. Data privacy relates to location and destination tracking by third parties. Cost of AVs relates to the additional costs for AV functionalities, whereas employment risks are typical for substitution of driver jobs by shared AV applications (Nordhoff et al., 2019).

The perceived benefits of AVs (i.e. perceived usefulness) are almost equally important to users' AV acceptance (Motamendi et al., 2019). Chapter 2 has delineated the positive direct and indirect impacts of AVs, which are mostly related to increased safety, accessibility, environmental benefits, reduced congestion, more comfort and cost reductions for individuals.

Subsequently, Nordhoff et al. (2019) has formulated a comprehensive process of a road users' Automated Vehicle Acceptance, that provides the actionable focus areas for user acceptance efforts. Three main stages are distinguished: exposure to AV, evaluation of AV and intention to use AV. The evaluation stage of AV is divided into three subprocesses or focus areas for the roadmap purpose: domain-specific system evaluation, symbolic-affective system evaluation and moral-normative system evaluation (see Figure 14). Not only does this comprehensive overview provide focus areas of 'soft' user acceptance building efforts, it also

[10] http://www.drive2thefuture.eu/

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provides user need requirements for infrastructure, regulation and vehicle design. For example, future demonstrations can formulate user acceptance KPI's according to these evaluation points.

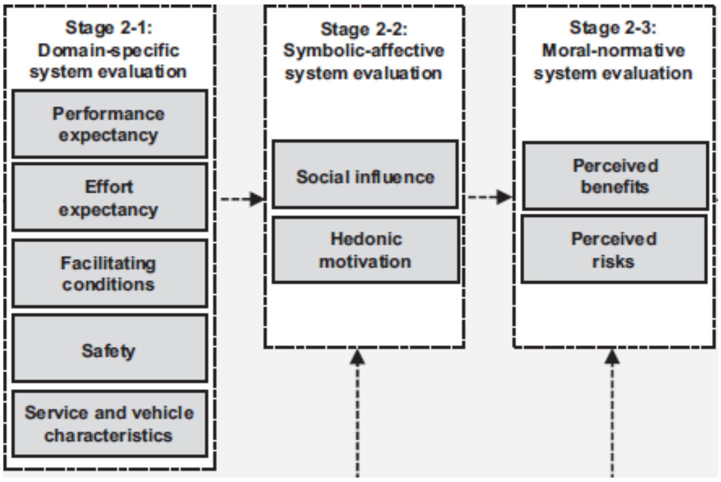

Figure 14: Subprocesses of a person's Autonomous Vehicle evaluation (Source: Nordhoff et al., 2019)

6.2 Key priorities and challenges

The deployment of large-scale demonstrations has been limited (CCAM, 2021), however, this shows to be the way forward regarding the user approach. The demonstrations considered for this roadmap are pilots, Field Operational Trials (FOT) and Living Labs. Like the SRIA 2021 roadmap by the CCAM partnership (CCAM, 2021), a close collaboration with other design developments is proposed to create an interplay between identification of user needs, whilst building user acceptance and AV driver experience. Some examples of useful interplay between design developments and demonstrations include:

- HMI improvements through targeted pilots on test tracks
- Recognition of physical infrastructure issues through FOT
- Recognition of flawed or missing regulations through living labs

The user approach is key for 1) building user acceptance and 2) retrieving design requirements from user feedback. Equally important to the proper function of AVs is 3) educating road users on using and coping with other people's AVs.

User acceptance & needs

Many user acceptance studies have been completed and the message is clear, as shown in 6.1. The strategic focus for user acceptance should be on alleviating people's regards of safety and security, closely followed by maximisation of the (perceived) user benefits and bringing down costs & associated risks. In other words, once safety and risk concerns are

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resolved and more trust is settled, AVs should deliver a commercially competitive alternative to non-AVs.

Much potential still lies with deploying AV demonstrations. Most people are inexperienced and generally uneducated on AVs (Garibaldi et al., 2021). Simultaneously, drivers who have experience with either Adaptive Cruise Control (ACC) or AV simulation or test rides show more trust regarding AVs ((Kyriakidis et al., 2015); (Hartwich et al., 2019); (Xu et al., 2018)). In other words, drivers who have experienced some form of ADAS are more trusting. This finding offers an important rationale for the deployment of demonstrations.

Therefore, to build user acceptance, retrieve user needs and train users, the user approach should build gradually on the incremental introduction of automation levels. Thereby making use of lower automation levels on limited ODDs to build trust and make users acquainted with AVs, before advancing to higher levels of automation in more complex environments.

User needs for design have not yet been studied thoroughly. That is what the CCAM partnership also underlines in their iterative approach in their 2021 roadmap: make use of iterative cycles between design and retrieving user needs/validation. Most AV user research so far has focused on user acceptance of AV technology, without eliciting reactions to design alternatives. Moreover, most test subjects did not experience actual simulators or AV ride experiences before or during the study ((Jing et al., 2020); (Kaye et al., 2021)). This could greatly improve our knowledge and provide more definitive answers to the specific needs of users. Here, user acceptance studies could provide useful guidance for deepening our knowledge. The comprehensive overview by Nordhoff et al. (2019) serves as an example for the focus areas.

<u>Educating road users</u>

Driving an AV requires training, since its handling requires drivers to develop a new 'mental model' and procedural skills. Mental Models are a person's model, internal representation, knowledge and understanding of the physical world, the behaviour of a system or the automation (Saffarian et al., 2012). According to training developed by Merriman (2021) drivers need to learn about: capabilities and limitations of the automation, how the automation works, how to activate and deactivate the automation, how to perform a takeover request.

Parallel to the demonstrations, a driver training system should be developed. Namely, from the (few) completed AV demonstrations and simulations, it shows that AV driver training is useful for building user acceptance and necessary to prepare drivers for handling AV's. Since driver training efforts are implemented permanently for existing and new road users, user acceptance and AV driver experience is extended to people who have not encountered AV through demonstrations. The EU directive 2006/126, implemented in 2013, already acknowledged the need for updating drivers with regards to ADAS (European Commission, 2017).Currently, the European Driving Schools Association, are planning to involve AV in a new training model (Picardi, EFA, 2020).

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Importantly, demonstrations will reveal the required amount of training and level of certification required for AV road users. The EU-funded SHOW[11], HADRIAN[12] and Drive2theFuture projects are already making efforts in this direction, among others.

6.3 The way forward

When facing the challenge to increase users' CAVs-readiness, the first things researchers, developers and public authorities should focus on are described in the table below.

Table 5: Major identified breakthroughs for user approach

Code	Category	Breakthrough
UA1	Driver training	Publicly deployed AV driver training system
UA2	User acceptance & needs	User needs topic are elaborately specified and validated, providing comprehensive lists of important decision-making factors.
UA3	User acceptance & needs	Sufficient user acceptance to support business model projections

[11] https://show-project.eu/
[12] https://hadrianproject.eu/

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7. Business models

7.1 Where are we today?

The developments mentioned in this chapter are related to the sustainable development of AV business models from both the public and private sector perspective. Whereas investments in AV infrastructure are most likely financed by the public sector, cost items like R&D efforts, fleet acquisition and licensing costs are the private sector's concern. The public sector will need a cost-benefit justification for investments made, whereas the private sector will require entirely new business models (ranging from partnerships, value propositions to different revenue streams). Moreover, public and private business models will intersect where the public sector incentivises/discourages certain aspects of private business models.

The output of this chapter, a vision forward, is focused on developing a sustainable AV financing model from the public and private perspective. Here, we try to formulate an approach which proactively scans the horizon for upcoming business models, to anticipate and address their socio-economic impacts as well as validate their sustainability.

In order for AVs to permanently penetrate the current automotive market, a stable business model must be formulated. Typical to most innovation, a stable business model is likely to emerge after a period of learning and co-creation by all involved stakeholders. After some period, an aligned vision and mission will be set to break through the current automotive market (Geels, 2011). In the alignment phase of upcoming innovation, it is key for both the public sector and private sector to achieve abovementioned goals. Thereby, a sustainable alignment between private and socio-economic impacts can be formed.

<u>Private sector: Currently emerging Business Models</u>

With the emergence of (shared) AV, the car industry is changing from a traditional technological monolithic structure, towards new business models (Nikitas et al., 2019). Here we delineate two types of perspective on currently emerging business models: the customer and supply perspective.

From the customer perspective:

Different forms of business models are available from the customer perspective. These differ mostly in ownership, pricing and degree of comfort (Avramakis et al., 2018).

Ownership of an AV is likely to differ from current car ownership. Either users purchase their own AV or make use of ride-hailing services by fleet operators, where the latter seems more promising for the short term. Namely unit prices of AVs have been estimated between $10.000 and $40.000 and the willingness-to-pay for AV services does not match those prices for most people, see Figure 15. These prices are expected to drop rapidly with growing market penetration though (Elvik, 2020). The dominance of fleet ownership over personal ownership

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is already showing, with OEMs currently prioritising Robo-taxi´s (fleet ownership) over private AVs (McGrath, 2020).

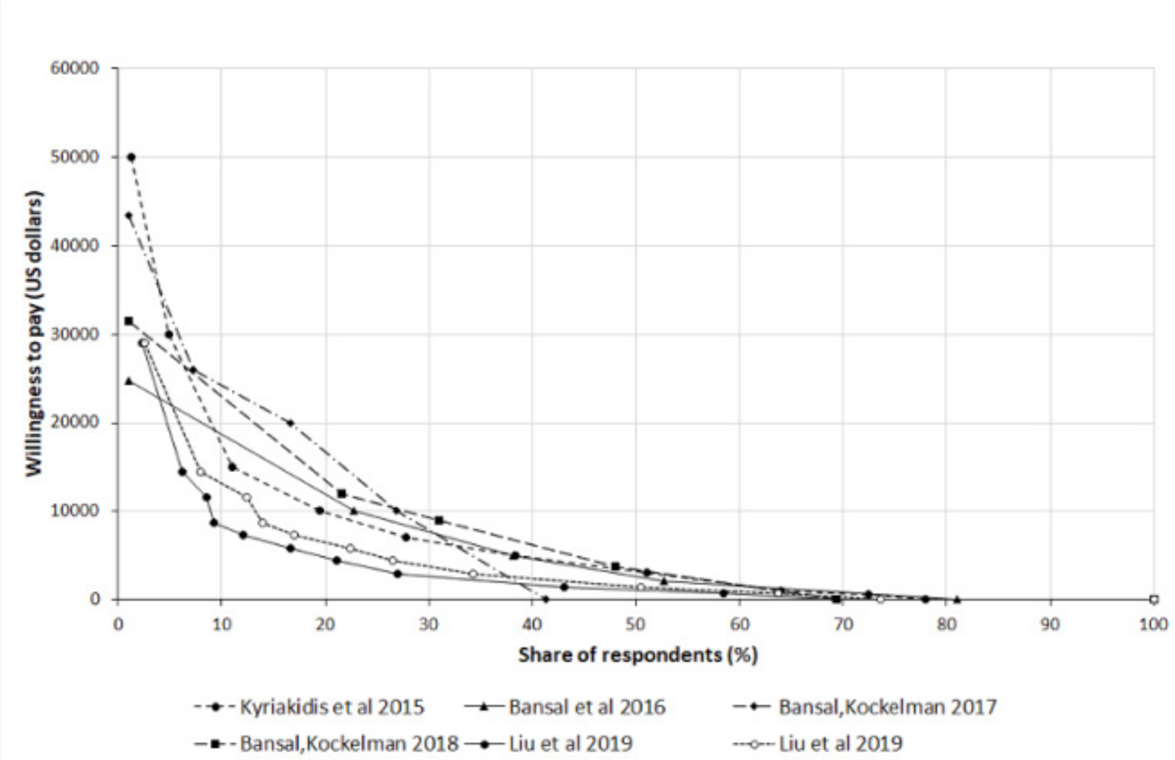

Figure 15: Willingness-to-pay for AV services (Source: Elvik, 2020)

Pricing relates to the payment scheme deployed for car usage. Alternatives which have so far emerged include pay-per-ride robo-taxi´s (i.e. driverless ride-hailing services) and subscription packages. An innovative idea behind the latter is the ability to rent out one´s AV for robo-taxi services when not using it themselves. This would allow AV ´owners´ to earn back their ownership costs. An important note here, is that these types of services would at least require a L4 (conditionally autonomous) or L5 (unconditionally autonomous) AV. Robo-taxis would otherwise not differ from regular ride-hailing services with driver.

Comfort for the consumer includes service aspects like infotainment and interior design, as well as the exclusivity of the transport. E.g. some services will be focused on private transportation for single travellers, whereas other services can focus on ride-sharing. It is expected that, these will differ in their prices.

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From the supply perspective:

Many aspects of a business model can be addressed from the supplier perspective. Here, three aspects are highlighted which have been getting much attention: reducing production costs, new OEM partnerships, and new revenue streams.

Because of the increased introduction of sensors, processing units, communication systems and driving algorithms in AVs, the total cost of such vehicles has been going up. As has been mentioned in 3.1, LiDAR cost will be one of the main costs driving the affordability of self-driving vehicles. For example, even though Waymo has been able to reduce the cost of its LiDAR sensor by 90% from $75.000 (in 2009) to $7.500 (in 2017), the need to include three of them still makes the vehicles expensive (VOLT, 2021). Moreover, the company's 5th generation car (May 2020) increased the number of LiDAR sensors from three to four, bringing higher costs. Some estimations place it around $180.000 (Moreno, 2021), which poses some challenges to achieve a widespread market penetration.

A significant shift is expected from mostly hardware-based value towards software-based value which creates the need for partnerships between OEMs and others (i.e. technology firm, ride-hailing services) (Alonso Raposo et al., 2018). Currently, about 90% of a car´s value is created from hardware and 10% from software. This is expected to shift towards 40% hardware, 40% software and 20% content (e.g. infotainment) (Gaenzle et al., n.d.). Many companies have joined forces, combining OEMS, mobility providers and technology firms (see Figure 16). By 2020, 159 partnerships had already been proposed by OEMS to share AV investment costs, which are substantial for interested OEMs (Möller et al., 2019).

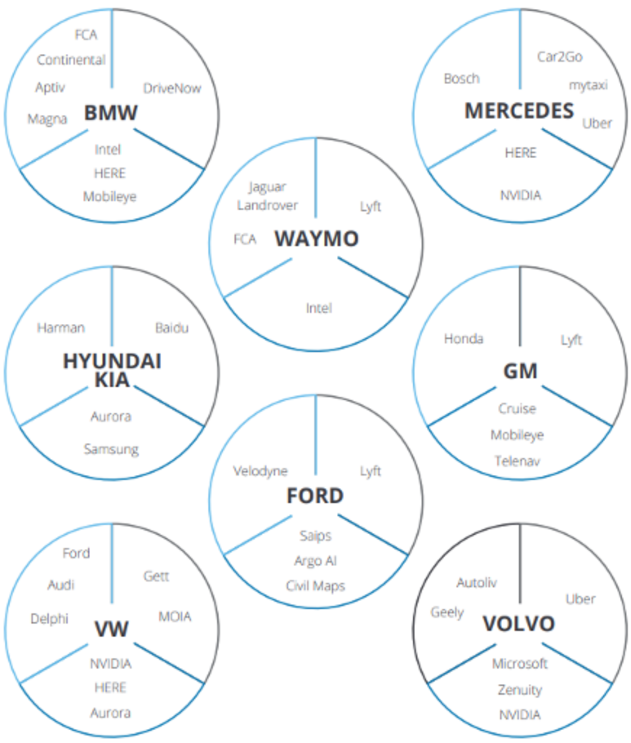

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Figure 16: Overview of OEMs partnerships (Source: Deloitte, 2019)

With the addition of sensors and transmitters to autonomous vehicles, new business opportunities (i.e., revenue streams) arise from additional generated data. Some examples include traffic information, real-time mapping, infotainment, telematics and data analytics. An eye-catching example is the interest by insurance companies to base insurance fees on people´s driving style (Wiggers, 2021).

Public sector: Socio-economic impacts

A range of socio-economic impacts caused by the introduction of AVs have been addressed in research. Milakis et al. (2017) have categorised socio-economic impacts in three tiers (see Figure 17). Several of the socio-economic impacts are yet uncertain, however, all of these are expected to change. The first tier, which is discussed here, comprises of travel cost implications, traffic implications and travel choice implications.

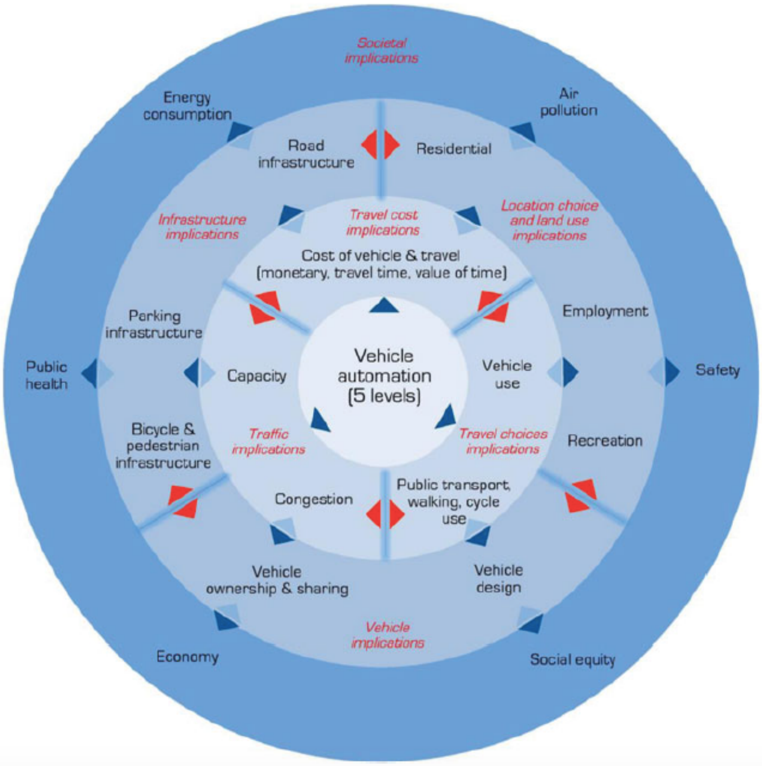

Figure 17: Tiers of socio-economic impacts (Source: (Milakis et al., 2017)

Travel cost implications relate to the decreasing cost price of AVs by economies of scale, reduced travel time, and reduced value of time due to increased productivity and comfort. Traffic and travel choice implications relate to choices of people and capacity reductions due to shorter inter-vehicle spaces. Interestingly, it is as yet uncertain what the consequences of AV on congestion are. On the one hand, it could increase due to increasing number of empty trips by robo-taxi´s. Especially the choices of people for ride-sharing instead of private car-sharing could have a positive impact on congestion (Ruter, 2019). However, several studies currently show that most people are not willing or comfortable to share AV rides (Cunningham

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et al., 2018; FTA, 2021). On the other hand, congestion could decrease due the increased road capacity through AVs (Alonso Raposo et al., 2018). In turn, the first tier, via the second tier, has a ripple effect on larger social themes: economy, safety, public health, air pollution, social equity, and energy consumption. Compared to other tiers, third tier effects remain less predictable since several second tiers have mitigating relationships.

Of the third-tier AV effects, arguably the most relevant is the expected safety gains. Since human errors make up over 90% percent of car crashes (Euro NCAP, 2017), removing control from the human´s hands is expected to increase road safety significantly (Milakis et al., 2017). Thus, achieving ´Vision Zero´, no more road fatalities by 2050, is here regarded as a separate entity besides the monetized ´value´ of increased safety typically formulated in Cost-Benefit Analyses.

7.2 Key priorities and challenges

The key challenge which currently revolves public & private business models is dealing with their uncertainty. For example, the uptake of shared and private AVs (vital to business model success) is dependent on factors like perceived safety & usefulness (see chapter 6). However, such criteria are dependent on still to be developed technologies and business models. Therefore, it is important to get an idea on the viability of the business models which are emerging now. Projects like the EU-funded SHOW have started in this area, covering pilots in 20 European cities.
There are two goals to achieve a long-lasting legacy for Autonomous Vehicles.

Assess and address socio-economic impacts

It is not yet clear how large socio-economic impacts will be, although several studies have tried to simulate or estimate their size (Alonso Raposo et al., 2018; Ruter, 2019). Moreover, unexpected impacts can still emerge from demonstrations. On the one hand, the ´business model´ for the public sector needs to be defined through identification and monetary valuation of socio-economic impacts in cost-benefit analyses. On the other hand, the socio-economic impacts can/ should be regulated, which improves the public sector's 'business case'. Of course, negative impacts should be minimised, and positive impacts maximised.

Another important complicating factor is the difference between socio-economic impacts of different automation levels. Especially as the difference between level 4, 5 (no driver needed for fallback operation) and the others is large. Only under level 4 and 5, no driver is needed behind the steering wheel. This opens up many applications (e.g. car-sharing) and accessibility for different user groups without driver licenses (e.g. youngsters, disabled and elderly). Lower automation levels will still require a driver present. Also, differences exist between level 4 and 5, relating to the situations under which automated driving is possible. For example, a level 4 AV may not be able to driver in adverse weather conditions, which limits its accessibility.

Here, it is key to ensure coordination between the public and private sector is tested in large-scale demonstrations. Swift but responsible growth of AV should be facilitated by this

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coordination, meaning that coordination should safeguard public interests whilst facilitating swift private sectors growth.

Create sustainable private business models

Complexity has increased considerably and learnings are scarce for AV business models (McGrath, 2020). As discussed a new customer and supply approach need to be formulated for the AV market. For OEMs this means stepping into unknown territory, which is inherently risky given the uncertainties attached. Moreover, the long-term viability, and therefore learnings, of business models in similar and neighbouring markets are also uncertain. Business models of the largest players in the ride-hailing market (e.g. Uber, Lyft) have only reported losses, with a focus on investments and economy of scale (Furcillo, 2020). Even though Uber has shown large market uptake, the question remains if their business model can become profitable (Chauhan, 2020). Interestingly, removing driver costs from ride-hailing services (by AV) could turn the tide for ride-hailing services joining the AV market (Uber, Lyft, Baidu).

In addition, insurance companies would need to adapt their policies and approaches to accommodate AVs. As drivers become less responsible for road safety, a bigger part of the liability cake will shift to manufacturers, component suppliers, and technology developers involved in building CAVs. Consequently, the current traditional approach to auto liability will need to allow more product-related liability coverage. The challenge still revolves around defining who is at fault in the event of an accident. Information about vehicle’s ODD definition and self-understanding of it, perception and decision algorithms, driving monitoring systems, and connectivity will be crucial to define who/what is responsible. If the vehicle’s is under human driver control, personal auto coverage will apply. If the vehicle is driving autonomously, liability shifts to product liability held by OEMs (Carlson, n.d.).

Economically speaking, the disruption of CAVs will also decrease the number of individual policies, in part because the vehicles will be owned by OEMs and/or other service providers like ride-sharing companies. On top of that, the policy price could also be reduced since autonomous vehicles will be considerably safer than human-driven vehicles, leading to reduced claims. A study from Accenture predicts that auto insurance premiums could dop by $25 billion by 2035 (Accenture, 2017). However, the study also points out that new revenues based on new insurance product lines, could compensate part of the losses, but that in the long-term, lost premium revenues will outweigh the gains. Nevertheless, this situation might create new opportunities for insurers, principally in three areas: cybersecurity, product liability for sensors and/or algorithms, and insurance against infrastructure (Accenture, 2017).

Thus, similar to the user approach and socio-economic impacts, it is key to reduce uncertainty and validate new business models via large-scale and preferably long-term demonstrations.

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7.3 The way forward

When referring to the Business Models' pillar, the main challenges and breakthroughs that will positively contribute to the introduction and sustainability of CAVs, can be observed in the table below.

Table 6: Major identified breakthroughs for sustainable business models

Code	Category	Breakthrough
BM1	Socio-economic impacts	Financially positive Cost-Benefit Analysis
BM2	Socio-economic impacts	Improve road safety achieving Vision Zero
BM3	Socio-economic impacts	City or region level public-private AV policies to address socio-economic impacts
BM4	Private business models	Validated & viable private business model(s)
BM5	Private business models	New insurance policies

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8. Holistic approach

The aim of this holistic approach is to understand the interrelationships between the pillars and to create an understanding of the sequence between breakthroughs. This chapter describes the synergies between pillars that define the holistic approach for CAVs introduction, while indicating a timeline for the achievement of different key breakthroughs.

8.1 Method

Firstly, a collated table containing all the identified breakthroughs in each pillar is presented. For simplicity, Table 7 shows a summary and the coding of the breakthroughs formulated in the report.

Secondly, the pillars from this roadmap are plotted against each other in a matrix format. Subsequently, the formulated breakthroughs are used to show the causal or sequential relationship between breakthroughs in pillars. The matrix (section 8.2) is supposed to be read from top to bottom, for every column. Each cell indicates how a breakthrough point in a pillar (column) enables progress in the other pillars' breakthroughs (rows).

So, if a cell is empty, it would mean progress in the respective pillar (i.e. column) is not a direct or important prerequisite for another pillar (i.e. row). The opposite is true for a cell that does contain information. Of course, multiple breakthroughs of one pillar could have an influence on one other pillar.

As an example, let's take the cell in the intersection between "vehicle technology" (row) and "infrastructure" (column). The first connection *"I1: Maintenance standards, reinforce vehicle's capabilities (VT1, VT2)"* means that if breakthrough I1 (*Increased maintenance standards, ensuring that CAVs ability to drive is not impaired by infrastructure deficiencies)* is achieved, for example with proper lane markings or clearly visible road signs (eliminating inferences like vegetation), it will create a positive contribution into improving the robustness of the perception system (VT1). Having a more robust perception system thanks to properly maintained infrastructure could in turn relieve some pressure from the vehicle's point of view by simplifying/eliminating some sensor suite's redundancies or required precision levels, bringing down the overall cost of the perception system (VT2).

However, this way of showing the relationships between pillars through the breakthrough points has some limitations. Relationships between three breakthroughs from different pillars need to be repeated in the respective cells, which can be less intuitive. To overcome this, a graphical visualisation of the relationships could be used. In addition, relationships could be weighed to show the level of importance compared to other relationships. Such weighs could be assigned in a qualitative or a quantitative (using predefined parameters) way, or through a combination of both.

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Table 7: Summary of breakthroughs

Code	Breakthrough
Vehicle technology	
VT1	Sensor suite robustness to expanded ODDs (all weather conditions, range of speeds, types of roads, etc.)
VT2	Affordable perception system costs while ensuring reliability and safety
VT3	Scenario independency for a more efficient and safe driving
VT4	Harmonisation and catalogue of ODDs, how does the vehicle understand them, and fail-operational architectures
VT5	Definition and standardisation of connectivity requirements for each ODD
VT6	(Cyber)secure and safe communications respecting privacy and trust
VT7	Definition of agreements and trust levels of OEMs between other OEMs, infrastructure, and other road users (VRUs)
VT8	Improved computation and storage systems
VT9	Seamless control transfer between vehicle and driver
Infrastructure	
I1	Increased maintenance standards, ensuring that CAVs ability to drive is not impaired by infrastructure deficiencies
I2	Improved and robust infrastructure safety measures to mitigate potential AV malfunctioning
I3	Defined and standardised interactions between digital infrastructure and CAVs
I4	Validated communication framework while investigating the benefits of common infrastructure classifications (i.e. ISAD)
I5	Defined financing models to establish the role public (road) authorities should take
I6	Defined Traffic management strategies
Regulation	
R1	Create a common type approval at EU level based on CAVs' needs, updating current procedures. Defined ODD catalogue.

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Code	Breakthrough
R2	New validation methodologies (simulation and virtual testing) included in safety assessments to reduce time and costs (required test kilometres)
R3	Methodology for testing new software systems, including AI and ML
R4	Rules of road established for shared spaces in urban areas
R5	Clear data sharing environment definition (what data is collected, how it is collected, how is it stored, who is the owner, etc.)
R6	Standardised approach of failsafe operation systems in case of cyber attack
R7	Developed Cyber security regulations
R8	Harmonise traffic rules and infrastructure requirements (physical & digital) at EU level
R9	Clear legal framework established (including the ODD, fault analysis, and human interaction) to determine who is responsible for each situation
R10	New driver training permits including the interaction with different SAE levels and ODDs
User Approach	
UA1	Publicly deployed AV driver training system
UA2	User needs topic are elaborately specified and validated, providing comprehensive lists of important decision-making factors.
UA3	Sufficient user acceptance to support business model projections
Business Models	
BM1	Financially positive Cost-Benefit Analysis
BM2	Improve road safety achieving Vision Zero
BM3	City or region level public-private AV policies to address socio-economic impacts
BM4	Validated & viable private business model(s)
BM5	New insurance policies

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8.2 Holistic interrelations

Table 8 presents the interrelations between the pillars´ breakthroughs. Two types of relations are present in the matrix:

- Sequential
  These relations are strictly chronological, with one or more breakthrough(s) proceeding other breakthrough(s). For example, development of an ODD catalogue and updated regulation precede the institutionalisation of an AV driver system.
- Continuous
  A development under one breakthrough influences developments under other pillars but does not necessarily precede it. Breakthroughs with continuous relations occur semi-simultaneously and can have a two-way causality. For example, infrastructure developments and demonstrations will reveal certain traffic management opportunities and socio-demographic costs/benefits, which influences the monetary justification for further infrastructure development.

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Table 8: Interrelations between pillar breakthroughs

	Vehicle technology	Infrastructure	Regulations	User Approach	Business Models
Vehicle technology		- I1: Maintenance standards, reinforce vehicle's capabilities (VT1, VT2) - I3, I4: Standardises V2I requirements to enable seamless connectivity (VT5, VT3)	- R1, R2, R3, R6, R7: Strong regulations could give directions to tech developers (VT1, VT4, VT6, VT9) - R8: Connectivity requirements (V2V, V2I) to ensure scenario independency (VT3)	- UA2: User needs are necessary for a well-aligned HMI (VT9)	
Infrastructure	- VT1: More robust perception systems might require less infrastructure investment (I5) - VT5: Inform deployment (I3) & investments needed (I5)		- R5: Established data ownership and sharing regulations catering the benefits of V2I (I3, I4) - R8: Regulations accommodating new infrastructure requirements to guarantee investments and deployment (I1, I2)		- BM1: A positive CBA is needed to justify infrastructure investments (I1, I2, I4)

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	Vehicle technology	Infrastructure	Regulations	User Approach	Business Models
Regulations	- VT1: More robust perception systems (can inform requirements and standards) (R1, R2) - VT4: ODD standardisation would facilitate type approval, liability assessment, and new driver training (R1, R6, R9, R10) - VT5: Inform public (road) authorities and OEMs on the role they need to take to ensure connectivity (V2I, V2V) (R5, R8, R9) - VT1, VT2, VT6, VT9: Proven safe technology can inform requirements, standards, and type approval (R1, R6, R7) - VT5: Connectivity requirements established will inform harmonisation of regulations (R8) and the establishment of clear roles and responsibilities (R9)	- I1, I2, I3, I4: Infrastructure R&D will inform regulators about the measures they need to take (where and how to establish rules/standards) (R4, R8) - I3, I4: Connectivity validation will allow proper standardisation (R5, R7, R8, R9)			

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	Vehicle technology	Infrastructure	Regulations	User Approach	Business Models
User Approach	- VT1: More robust sensors across ODD´s creates more user flexibility (UA3). - VT4, VT9: Standardised human-driver role and limitations of ODDs increase trust and ease-of-use (UA3) - VT4 & VT9 HMI and ODD standardisation support driver training (UA1)	-I2: Forgiving infrastructure for AV malfunctioning increase perceived safety (UA3)	- R1, R2, R5, R7: Creating trust and encouraging adoption through vehicle certification, HMI standardisation and cybersecurity regulation (UA3) -R1, R2 Standardised HMI and AV behaviour guarantees human adaptation across car designs (UA2) - R4, R8: Mixed traffic rules necessary to develop driver training (UA1) - R10: Institutionalised driver training system (UA1)		- BM2 proved road safety track record will generate trust among users and increase adoption (UA3) - BM3 validated business models are needed to create higher user acceptance (UA3)
Business Models	- VT1, VT3, VT4, VT5, VT6, VT7, VT9: Will ensure improved safety (BM1, BM2) - VT5, VT6, VT7: Improved traffic management opportunities (BM3) - VT2: Cost-efficient technology (e.g. sensing system) supports Business Model viability (BM3)	- I1: Well-maintained infrastructure ensures safe AV operations (BM1, BM2) - I2: “Forgiving” infrastructure to compensate for AV errors/behaviour/crashes and increase safety (BM1, BM2) - I3: V2I as a safety enabler (BM2) -I5: Identification of infrastructure costs to support CBA (BM1) -I6: Increase of traffic management opportunities (BM3)	- R1, R4, R6, R7, R8, R10: Regulations ensure safety benefits (BM2) - R4, R8: Regulatory framework enforces local (city, regional, national) policies (BM3) - R1, R2: Regulations create a clear path and trusted investment climate for businesses and investors (BM4) - R1, R7, R9: Clear responsibility framework will inform new insurance policies (BM5)	- UA1: New driver training systems will improve AV safety benefits (BM1, BM2) - UA2: Specific user needs are central to create and validate business models (BM3)	

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8.3 Indicative timeline

Even though it's commonly accepted that setting a timeline for the development of CAVs is a hard task, we believe it can be of use to indicate when some of the challenges or breakthroughs listed could be achieved.

The extended benchmark performed together with the interviews were used as a reference point for the indicative timeline. As mentioned in this report, much uncertainty still exists for the timeline of breakthroughs, varying in size. In the coming years more certainty will arrive for several pillars of the AV roadmap, following pilots and large-scale demonstrations. To cope with such uncertainties, it is wise to add time brackets instead of saying then certain technology will be ready or certain challenge will be solved in a specific time.

Under Table 10, the indicative timeline for breakthroughs under the pillars is presented. The main takeaways for the timeline are 1) the sequence of breakthroughs 2) rough estimated time it takes to reach a breakthrough 3) a rough indication of developments until 2050.

For simplicity, some breakthroughs have been grouped together under a common category. The categories, which can be observed in the rows of Table 9, and their associated breakthroughs are the following.

Table 9: Included breakthroughs in each category for timeline

Category	Included breakthroughs
Vehicle technology	
Perception systems	VT1, VT2
Driving systems	VT3, VT4
Connectivity	VT5, VT6, VT8
HMI	VT9
Infrastructure	
Maintenance standards	I1
Road geometries, design	I2
V2I communication requirements	I3, I4
Financing models	I5
Traffic management	I6
Regulations	
Vehicle type approval	R1, R2, R3
Traffic rules & infrastructure requirements	R4, R8
Data management & legal framework	R5, R9
Cybersecurity	R6, R7
Driver training institutions	R10
User Approach	
Driver training system	UA1
User needs	UA2

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Category	Included breakthroughs
User acceptance	UA3
Business Models	
Cost-Benefit Analyses	BM1
Safety and Vision Zero	BM2
Socio-economic impact measures	BM3
Private business model	BM4
Insurance policies	BM5

Overall, the following trends can be observed:

- Vehicle technology developments should start now. Short-term priority lies here.
- Physical infrastructure improvements precede digital improvements. More room for improvement and pressing needs in maintenance standards, digital infrastructure can further enhance CAVs driving. V2I communication succeeds data regulation. Financing models follow after more experience with CAV impacts allows the quantification of infrastructure needs. Finally, when a considerable number of CAVs is deployed, improved traffic management strategies can begin to take place.
- Regulations can either act as a follower or a pusher. In terms of vehicle type approval, regulations will follow the developments under the vehicle technology pillar, always providing room to accommodate new technologies. For the infrastructure, they will act more as a pusher, ensuring that CAV's needs (demonstrated in pilots, FOTs and living labs) in terms of infrastructure, are satisfied. For the human driver training, once the first vehicles start reaching the market and the user needs start to be defined, the first regulations can start, which will last quite some years, being adapted as new automation levels penetrate the market.
- For a large part, the User Approach closely follows and runs simultaneous to Vehicle Technologies. Driver training systems can start to develop after the first Regulatory developments and thereafter closely follow Vehicle Technology developments, to finalize before the large uptake of higher automation levels. User needs support Vehicle Technology developments, whereas user acceptance is built continuously by pilots, demonstrations along the entire timeline.
- Business model developments are likely to be more responsive because progress can only be made after more certainty is created under other pillars. Successful public AV policy, CBA´s and private business models will take shape following validated vehicle technologies, regulatory certainties, and more AV user uptake in society.

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Table 10: Indicative timeline for the five pillars

	2025	2030	2035	2040	2045	2050
Vehicle Technology						
Perception systems						
Driving systems						
Connectivity						
HMI						
Infrastructure						
Maintenance standards						
Road geometries, design						
V2I Communication requirements						
Financing models						
Traffic Management						
Regulations						
Vehicle type approval						
Traffic rules & infra requirements						
Data mgt. & legal framework						
Cybersecurity						
Driver training institutions						
User approach						
Driver training system						
User needs						
User acceptance						
Business Models						
Cost-Benefit Analyses						
Safety and Vision Zero						
Socio-economic impact measures						
Private business model						
Insurance policies						

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8.4 Additional alignment

The final key to the well-aligned development of the pillars are demonstrations and testing. The demonstrations considered for this roadmap are pilots, Field Operational Trials (FOT) and Living Labs. Like the SRIA 2021 roadmap by the CCAM partnership, a close collaboration between the pillar´s design developments and demonstrating/testing is proposed. Some examples of useful interplay between design developments and demonstrations include:

- HMI improvements through targeted pilots on test tracks
- Recognition of physical and digital infrastructure issues through FOT
- Recognition of flawed or missing regulation through living labs

Moreover, the interplay between design developments of different pillars is also necessary to advance AV development. For example, driver training systems must adapt to changing HMI developments and ODD expansion. Therefore, it is key to leverage demonstrations by combining connected developments of the pillars into shared demonstrations.

Demonstrations are to be built up gradually in size and scope. Targeted and small-scale pilots with 1 to 20 cars can be useful to identify unforeseen issues or validate subsystems. Field Operational Trials have an increased size and scope, which are considered to require at least 100+ vehicles and usually have a time span of weeks to several months (FOT-NET, 2010). Logically, subsystems that can be tested on small-scale pilots should be validated before this stage. Lastly, living labs have the largest scale and time span (several months to several years). Whole communities partake in living labs, thereby creating the richest source of data. Long-term effects can be observed under living labs. For example, socio-economic impacts, the success of driver training systems, as well as the social influence on AV adoption can be observed here. Demonstrations can be assessed using the M^3ICA framework developed by the SHOW project (Anund et al., 2021).

Fortunately, there is an incentive for both sectors to collaborate in testing: the private sector needs permits and places to test technology and business models, whereas the public sector needs future AV service providers to test infrastructure, regulations and AV policies. Under the CCAM partnership, stakeholders are encouraged to provide unique assets for demonstration purposes (e.g. vehicle fleets and data by OEMs, 5G by network providers) (CCAM, 2021).

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8.5 Mapping of key CCAM challenges and breakthroughs to SAFE-UP expected outcomes

SAFE-UP project builds upon several breakthroughs and challenges identified in this roadmap. A mapping exercise is attempted in this section. However, it should be noted that this exercise is at a descriptive level at this stage, whereas a more detailed analysis of the SAFE-UP position on future mixed traffic situations, will be further investigated in deliverables D7.5 and D7.6, considering this document as a baseline.

First of all, the definition of safety-critical scenarios in WP2 by means of simulation (R2) and accident analysis, will allow to understand and quantify better the potential socio-economic impacts of CAVs (BM3), specially focused at road safety (BM2).

Regarding the different Demos, Demo 1 will contribute to improve passenger safety (BM2) considering new seating positions and HMI (VT9) and considering new testing methodologies (R2). Demo 2 will contribute on the progress to achieving more robust and reliable perception systems (VT1), specially improving VRU detection under bad weather conditions. Demo 3 will contribute to avoid crashes (BM2) by combining advanced steering and braking manoeuvres based on the perceived environment (VT3). Demo 4 will take advantage of the benefits brought by vehicle connectivity to warn VRUs about imminent safety-critical situations (BM2) through real-time communication. Connectivity requirements and protocols will be established for accident avoidance in the respective ODD (VT5, I3, I4).

In WP5, new testing methodologies for the active (WP3) and passive (WP4) safety systems will generate knowledge on the future automated vehicle type approval (R1, R2, R3) and will demonstrate and validate the expected improvement of road safety (BM2, BM3) in the future scenarios identified in WP2.

WP6 will contribute to develop strategies to raise awareness of VRU risk in current and future safety-critical scenarios identified in SAFE-UP according to increasing implementation of advanced driving function. It will contribute positively to address the user needs (UA2) and generate knowledge to assess the future driver training schemes (R10, UA1).

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9. Conclusions

The path to CAVs is still uncertain and several challenges remain to be solved, as reflected in the thematic discussions under each pillar,

In relation to vehicle technologies, solving the challenges around the perception and decision systems would allow a more effective and safe integration of CAVs. In addition, the connectivity requirements between the vehicle and its surroundings (V2V, V2I, V2X) still need to be tested, proven, defined, and standardised.

Following technological developments, regulatory bodies should ensure that the benefits of CAVs are capitalised, by creating the necessary frameworks to promote research and validation to guarantee user's safety and effective vehicle integration in the transport system. Additionally, a user-centric approach cannot be forgotten, and their needs and acceptance need to be further investigated, which will boost adoption and the consequent benefits brought by CAVs. At the same time, sustainable business models are crucial to ensure a long-lasting legacy of such benefits.

All in all, the importance of the holistic approach has been underwritten by this roadmap. Coordination and collaboration between the different pillars of AV is paramount to its development. Whereas every pillar, represented by its own stakeholders, has individual developments to complete, they show to be interlinked, and the whole path to vehicle automation cannot be achieved if one of the pillars fails. Strictly sequential relations between pillars´ breakthroughs are identified, as well as continuous relations that reinforce others over time.

Validation through testing and demonstrations is closely linked to most breakthroughs. Demonstrations are a stage apart from development and key to validate design choices. Moreover, they are to be used for benchmarking and communicating developments in the different pillars. Here, a formal protocol for the processes involving demonstrations can strengthen coordination between and intermediate strategy changes for involved stakeholders.

As further recommendations, this roadmap could be updated with more consensus. First, a deeper and more extensive review about the pillars could be performed. Secondly the identification of the key developments and challenges could be further extended and prioritised, as well as their translation into breakthrough points. Finally, the relationships between pillars could be further expanded and investigated, as new research and initiatives will provide fresh insights about how all the elements connect and influence each other.

As a result, the authors will work on regular updated versions of this roadmap, integrating latest technological, political, societal and business trends, to be finally compiled in two related deliverables under this same WP7 (D7.5 – Position paper, D7.6 – Exploitation results and business cases of SAFE-UP developments), both due in project month 36 (May 2023).

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