Expected impact of the deployment of Automated Vehicles in the EU

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Study on technology, regulation, and foresight

This study examines the future deployment of Automated Vehicles in the European Union through an analysis combining technological assessment, scenario development, and policy evaluation. Building on recent advances in Artificial Intelligence, Software-Defined Vehicles, and Intelligent Infrastructure, the study develops three scenarios – European Leadership, Selective Strengths and Dependencies, and External Dependence – to explore how Europe's regulatory and industrial position might evolve. These scenarios serve as a framework for assessing policy options related to legislation, deployment, and EU support for research and development.

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Executive summary

The deployment of Automated Vehicles (AVs) in the EU represents one of the most transformative developments in future mobility. It has the potential to reshape not only transportation systems, but also industrial competitiveness, research priorities, and social structures. This study examines how Europe can shape the introduction of AV technologies.

The study has three main objectives:

- to assess the technological and regulatory drivers influencing AV deployment in Europe;
- to explore possible futures for the EU through a set of structured scenarios; and
- to develop and evaluate policy options that could guide EU decision-making in this field.

The methodological approach includes an analysis of key research areas in AV technology, expert consultation, and foresight analysis. It is based on existing technological and regulatory knowledge and integrates findings from the fields of Artificial Intelligence (AI), Software-Defined Vehicles (SDV), and Intelligent Infrastructure, i. e. the three main pillars of automated driving.

Three scenarios were developed to illustrate different paths for Europe's role in the global introduction of AVs:

- Scenario 1: European Leadership. Through strong coordination and technological leadership, the EU is becoming a global leader in AV technology, regulation, and deployment.
- Scenario 2: Selective Strengths and Dependencies. Europe maintains excellence in selected domains but remains dependent on foreign technologies in critical areas such as AI hardware or data infrastructure.
- Scenario 3: External Dependence. The EU relies heavily on non-European developments, adopting external standards and technologies.

These scenarios serve as a framework for examining the social and economic impacts, the implications for research and development (R&D), and the transformative effects on public transportation systems. They also provide a structured basis for evaluating policy options related to legislation, deployment, and research funding.

Conclusion 1: Europe's main strengths in AVs lie in its regulatory frameworks and its expertise in safety, system integration, and reliable road-user interaction. A viable path for Europe is to use these advantages while continuously enhancing its assessment capabilities across all AV technologies. However, Europe should also identify and gain sovereignty over a defined set of 'critical technologies', i. e. the essential building blocks that must remain under European control, if AVs are considered as part of the critical infrastructure. To achieve this, it might be necessary for Europe to implement strategic industrial and R&D safeguards where required.

Conclusion 2: In the field of R&D, combining a limited number of European Centres of Excellence with a decentralised network of research institutions is likely to be an effective approach for maintaining Europe's ability to keep pace with technological advances in the United States and China.

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1. Introduction

1.1. Opportunities of Automated Vehicles

Automated Driving Systems (ADS) are expected to significantly increase the safety on the roads. Since more than 90% of the crashes can be attributed to human errors [1, 2], ADS have a huge potential to reduce accidents. A recent study from Waymo based on approx. 91 million kilometres of their ride-hailing service, i.e. without a driver behind the steering wheel, shows a large statistically significant reduction of intersection crashes compared to human drivers and no statistically significant disbenefit was found in any of the 11 considered crash type groups [3].

In addition to the potential of providing a higher safety level in traffic, AVs enable new services like robotaxis, i.e., ride-hailing, autonomous shuttles in public transport or autonomous freight transport and delivery services. From a social perspective, AVs promise not only greater safety but also improved access to transport for elderly people and people with disabilities. In rural areas in particular, AVs or autonomous shuttles can usefully supplement existing public transport services supporting a better access to essential services like shops or hospitals. In [4], where 49 review articles were analysed regarding the effects of AVs, advantages are seen on the economic level regarding potential cost reductions and productivity gains. However, high capital costs, labour displacement, and regulatory uncertainty are mentioned as possible risks. The study concludes that the sustainability of AVs depends largely on deployment strategies.

1.2. Purpose of the study

The Automated Driving Systems Regulation (2022/1426/EU) was adopted in 2022 and later complemented by the revised Intelligent Transport Systems (ITS) Directive (2023/2661/EU), adopted in November 2023. By implementing EU Regulation 2022/1426 on Automated Driving Systems, Europe leads globally in providing a clear and fully integrated legislative framework for the deployment of this new vehicle generation. Because Member States (MS) must adapt their national legislation to accommodate ADS, the Commission hosted a series of workshops to assist national regulators and encourage harmonised ADS deployment by presenting the latest status on relevant policy issues. The results of these workshops have been summarized in the document "Implementation of EU 2022/1426 Summary Report on Policy-related Topics" [5]. However, given the short time elapsed since the passing of the most recent legislation on the topic, a comprehensive ex-post evaluation would be premature and is more appropriately undertaken at a later stage by the responsible evaluation unit.

The purpose of the study is to assess the expected impact of deploying AVs in the EU by analysing key aspects of the current landscape of ADS and their regulatory environment. It examines the latest technological advances and their potential impact on the deployment of AVs. In addition, the study analyzes the legal framework for AVs and assesses the implications for R&D. In this way, the study also provides an understanding of the social, economic, and environmental impacts of the introduction of AVs in the EU. Based on this assessment, it focuses on two policy areas that are crucial to the success of AV deployment in Europe: (1) legislation and deployment, and (2) EU support for R&D.

1.3. Key concepts of the study

This study is based on four key concepts that serve as guidelines for analyzing the expected impact of AVs in the EU.

The first key concept addresses the technological drivers of automated driving. Advances in AI, SDVs, and Intelligent Infrastructure are shaping the future ADS. These technological drivers influence the pace at which AVs can be introduced, as well as the types of services and applications they enable.

The second key concept focuses on the regulatory environment in Europe, taking into account that technology and regulation are developing in parallel. The deployment of AVs depends on EU legislation, national implementation, and the ability of regulatory frameworks to keep pace with technical innovations. Understanding the current state and challenges of EU and MS regulations is important for assessing possible developments.

The third key concept is based on the use of scenarios to examine different developments for the deployment of AVs in Europe. The study introduces three scenarios, namely European Leadership, Selective Strengths and Dependencies, and External Dependence, to illustrate how differences in technological capabilities and regulatory alignment could shape Europe's role with regard to AVs.

The final key concept concerns the development of policy options. Based on the scenario analysis, the study focuses on two policy areas that are central to supporting the safe, effective, and competitive deployment of AVs in Europe: 1. Legislation and Deployment; 2. EU support for R&D. These areas form the basis for the policy options presented in the study.

2. Methodology

2.1. Main pillars of the study

The methodological approach of the study is based on three main pillars.

Pillar 1: Assessment of recent technological developments

The latest technological advances relevant to AVs are identified and analyzed. These include new AI methods such as end-to-end learning approaches and new system architectures such as SDVs. Their potential impact on the capabilities of AVs, safety assurance, system integration, and the suitability of existing regulatory frameworks is taken into account in the analysis. This pillar helps to identify areas where technological innovations may require regulatory adjustments or new policy support.

Pillar 2: Review of literature and EU legislation

A systematic review is conducted covering academic research, industry analyses, and EU legislation related to AVs. The review provides a consolidated understanding of the current state of AVs and the regulatory context shaping their development.

Pillar 3: Stakeholder interviews

Semi-structured interviews are conducted with a selected group of stakeholders, including industry experts, researchers, and representatives of relevant organizations. These interviews provide qualitative insights into stakeholders' experiences, their expectations for the deployment of AVs, perceived regulatory challenges, and their views on future technological development. These qualitative contributions complement the literature review and technology analysis.

2.2. Scenario-based consideration of future developments

Based on the three pillars mentioned in the previous subsection, the study provides a foresight analysis of how emerging technological developments may influence the deployment of AVs in the EU. To explore potential futures, three scenarios for the next 10–15 years are elaborated:

- Scenario 1: European Leadership. Through strong coordination and technological leadership, the EU is becoming a global leader in AV technology, regulation, and deployment.
- Scenario 2: Selective Strengths and Dependencies. Europe maintains excellence in selected domains but remains dependent on foreign technologies in critical areas such as AI hardware or data infrastructure.
- Scenario 3: External Dependence. The EU relies heavily on non-European developments, adopting external standards and technologies.

These scenarios provide a structured basis for assessing potential impacts, identifying challenges and opportunities, and subsequently developing policy options for the deployment of AVs in the EU.

2.3. Elaboration of policy options

Given the findings from the previous parts, the study addresses policy areas and, for each of them, policy options are elaborated and listed. The policy areas refer to:

1. "Legislation and Deployment" covering the regulatory frameworks, harmonisation efforts, and deployment strategies necessary to support the safe and coordinated introduction of AVs in Europe. This area also addresses the potential for a more protective market approach to secure European interests.

2. "EU Support for Research and Development" addressing funding mechanisms designed to strengthen Europe's technological capabilities and ensure a competitive position in the global AV landscape.

For each policy area, specific policy options are developed, considering the insights gained from technological drivers, regulatory analysis, and scenario-based foresight. These policy options are discussed in Chapter 5.

3. Synthesis of the research work and findings

This chapter presents the synthesis of the research conducted and key findings of the study. It provides a structured overview of the technological, regulatory, and strategic dimensions shaping the deployment of AVs in the EU. Section 3.1 examines the key technological drivers, including advances in AI, SDVs, and Intelligent Infrastructure. Section 3.2 briefly presents the current regulatory landscape in Europe with regard to AVs. Building on these findings, Section 3.3 presents three scenarios, namely "European Leadership", "Selective Strengths and Dependencies", and "External Dependence", which outline possible paths for the deployment of AVs in the EU. These sections provide a good basis for understanding the opportunities, constraints, and strategic considerations for developing policy options in Chapter 5.

3.1. Technological drivers of automated driving

3.1.1. Artificial Intelligence

AI plays a key role in AV development, first enabling robust perception in modular autonomous driving stacks and now driving research and commercial efforts toward end-to-end learning. In the traditional modular architecture, consisting of perception, prediction, planning, and control, AI has played a crucial role in enabling reliable environmental understanding. Recently many companies are exploring end-to-end approaches where deep learning models map raw sensor input directly to driving decisions. These approaches aim to improve the scalability and adaptability of AVs by using large datasets and learning frameworks.

Early and commercially deployed AV systems adopt a modular stack: sensors feed into perception models that detect and classify objects; predictions estimate the intent of other road users; planning modules compute safe actions; and control modules execute maneuvers. In these systems, AI and machine learning have replaced traditional manual-engineered vision pipelines with deep neural networks capable of real-time object detection, semantic segmentation, tracking, and predictive modeling in complex environments. Companies like Waymo exemplify this approach [6]. For over a decade, Waymo has used a diverse set of AI models for perception and prediction in its development and robotaxi fleets., relying on LIDAR, radar, and camera fusion paired with classical planning frameworks to achieve safe autonomy. *This modular architecture allows for rigorous verification and isolation of components, a key consideration for high-assurance safety in production systems*.

In contrast to modular pipelines, end-to-end learning integrates multiple tasks, such as perception, prediction, and planning, into a single learning framework. Early work on end-to-end learning for autonomous driving dates back to 1989, when a neural network was first used to control a vehicle [7]. The idea reemerged with DAVE in 2004, demonstrating obstacle-avoidance in cluttered environments [8]. NVIDIA's DAVE-2 followed in 2016 showing that deep learning could control real vehicles [9] and becoming a key reference for many modern end-to-end approaches. In recent years, several companies have moved from traditional modular driving systems toward end-to-end learning, where a single AI model learns to drive directly from raw sensor data. Tesla is one of the most prominent adopters of this approach: its Full Self-Driving system utilizes a foundational model that processes raw video input from cameras and makes steering, braking, and acceleration decisions without relying on many hand-coded rules [10, 11]. Wayve, a UK-based startup, follows a similar approach with its AI-driver platform, which learns general driving behavior from large datasets and operates without detailed high-definition maps [12, 11]. Waymo is also exploring this direction through its EMMA research project, which uses a large multimodal AI model to jointly understand the environment and plan driving actions in a single framework [13]. Chinese companies such as Momenta and Huawei are likewise developing integrated AI systems that combine tasks previously handled by separate modules. This reflects a broader industry trend toward more scalable, data-driven AVs. *The primary drawbacks of the end-to-end learning approach center on its "black-box" nature, which lacks the interpretability and explainability required for rigorous safety validation.* Validating these systems is difficult because it is nearly impossible to trace a specific failure back to a single root cause or rule, making traditional safety guarantees like ISO 26262 hard to satisfy.

Table 1 – Comparison of the end-to-end with the modular approach for AVs

Feature	End-to-end approach	Modular approach
Architecture	A single, unified neural network mapping sensor input directly to control signals.	A chain of discrete sub-modules (Perception → Prediction → Planning → Control).
Optimization	Jointly optimized: The entire system is trained to minimize a single driving-error goal.	Locally optimized: Each module is perfected for its specific task (e. g., object detection accuracy).
Development	Relies on massive data scaling and compute resources rather than hand-coded rules.	Requires significant human engineering to write and tune a large number of rules.
Efficiency	High: Shared computational modules reduce computational load and avoid "information loss" between steps.	Low: Data must be transformed and passed between modules, often leading to cumulative "propagation errors".
Safety and Debugging	Low: Difficult to determine why a model made a mistake; lacks clear intermediate outputs.	High: Engineers can isolate errors to a specific module (e. g., "the perception module failed to see the pedestrian").

Source: Produced by the authors.

3.1.2. Software-Defined Vehicles

SDVs are vehicles whose functionality and behavior are primarily determined by software that can be updated, expanded, and reconfigured throughout the vehicle's entire life cycle [14].

This paradigm shift in vehicle architecture, characterized by the consistent separation of hardware and software, enables greater innovation speed and better control of the increasing system complexity of automated vehicles [15], as these do not arise from isolated components, but from the interaction of highly complex software modules such as sensor fusion, environment modeling, behavior prediction, decision logic, and trajectory planning. The modules involved must interact in real time, monitor each other, and establish consistent environmental and system states. Classic, highly fragmented ECU distributions are structurally unsuitable for this close functional coupling.

A key feature of SDVs is the continuous development and updating of software functions via over-the-air updates (OTA), which enable vehicle functions to be adapted and expanded even after delivery [16]. This capability is now increasingly being implemented in production vehicles and is being explicitly pursued as a strategic development goal by several manufacturers. Within this context, Tesla stands out as an early pioneer of a software-centric vehicle architecture with extensive OTA capabilities. However, there is currently no uniform technical standard for clearly classifying a vehicle as an SDV. Instead, a maturity model with fluid transitions should be assumed, in which individual vehicles may already be considered SDV-like [15].

This development is particularly relevant in the European context, as automated and autonomous driving functions must not only be technically mastered, but also operated safely, traceably, and in compliance with regulations throughout the entire vehicle life cycle. Requirements for functional safety, Safety of the Intended Functionality (SOTIF), cybersecurity, and the controlled release and traceability of software updates make systematic versioning, validation, and monitoring of software absolutely essential. These requirements cannot be consistently met without software-defined vehicle architectures with a system-wide software lifecycle, making SDVs a key prerequisite for the introduction of autonomous driving functions in Europe.

The central and zonal E/E architectures underlying SDVs are gradually being introduced by leading Original Equipment Manufacturers (OEMs) as a prerequisite for continuous software updatability. These architectures consolidate computing resources on a limited number of high-performance computing platforms and are not based on a large number of function-specific embedded control units. Manufacturers such as the BMW Group and Mercedes-Benz are using centralized high-performance computers in their latest models to bundle and execute vehicle-wide software functions. At the same time, the Volkswagen Group is promoting zonal E/E architectures in which sensors and actuators are organized into regional zones and connected to centralized computing platforms. These architectural approaches enable strong decoupling of application software from the underlying hardware, support centralized orchestration of software services, and facilitate OTA updates within a continuous, system-wide software lifecycle.

On this architectural basis, containerized software approaches in SDV enable the decoupled updating of individual services without reflashing the entire system [14, 17]. In conjunction with permanent vehicle networking, this creates a closed, data-driven development cycle in which fleet data is used for continuous further development, especially of AI-based functions [14, 15]. New software versions can be validated in stages: While digital twins support virtual development pre-validation [17], shadow mode in the real vehicle allows passive evaluation of new algorithms under real traffic conditions before they are transferred to active vehicle operation in a controlled manner [14].

3.1.3. Intelligent Infrastructure

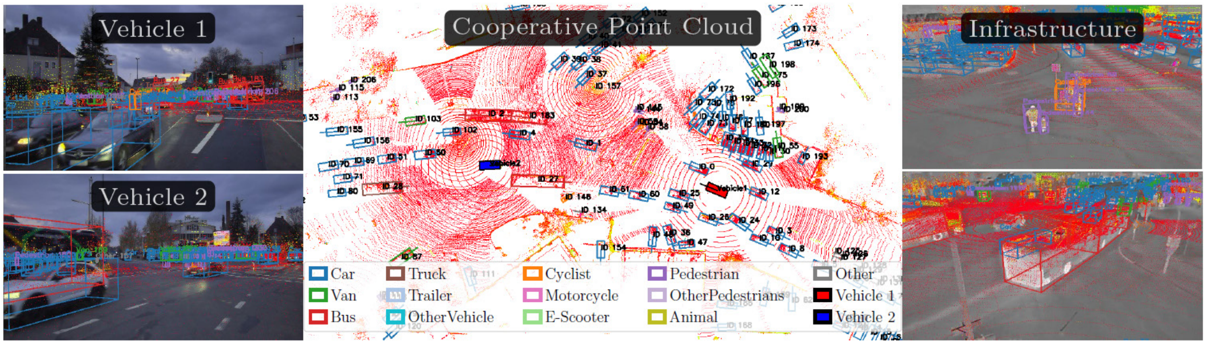
In this study Intelligent Infrastructure for AVs refers to roadside technical sensor equipment that detects complex traffic situations, interprets them using edge computers, and interacts cooperatively with vehicles via a communication system. With the help of cameras, radar, or LiDaR, it supplements the limited vehicle-based environment detection, allowing the Operational Design Domain (ODD) of Cooperative, Connected and Automated Mobility (CCAM) vehicles to be expanded [18, 19].

Especially in critical urban scenarios – such as occlusion situations, challenging detection of road users, and highly dynamic traffic situations – intelligent infrastructure can be an important building block for the robust and safe operation of AVs. Although it should not be assumed to be a mandatory prerequisite for autonomous mobility, it can significantly increase the safety, efficiency, and reliability of automated driving functions in specific situations [20].

Intelligent Infrastructure is usefully complemented by Cooperative Intelligent Transport Systems (C-ITS) technologies, which provide standardized communication mechanisms for the exchange of safety- and efficiency-related information between vehicles and traffic infrastructure. This communication is based, among other things, on established V2X radio technologies such as the ETSI ITS-G5 protocol stack, which utilizes IEEE 802.11p radio technology specifically designed for cooperative vehicle-infrastructure applications. The introduction of such C-ITS approaches is supported politically and programmatically in Europe, including as part of the European Union's ITS strategy [21]. While C-ITS primarily addresses cooperative communication in the transport system, intelligent infrastructure extends this approach to include infrastructure-side perception and on-the-spot processing, so that information can generated and processed in a context-dependent manner.

Against this background, the KIVI project in Ingolstadt for example, established and operated an intelligent roadside infrastructure in a real urban traffic environment [22]. A modular sensor and edge architecture was implemented at selected inner-city intersections, which continuously records the intersection area, interprets traffic flows, and makes them usable for cooperative applications. The operation of the infrastructure shows that the combination of infrastructure-based perception, local data processing, and cooperative information provision enables safety-critical situations in particular to be detected and addressed at an early stage. The KIVI project thus provides a practical example of the effects of intelligent infrastructure as a supporting component for the robust and safe operation of automated driving functions in an urban context.

Figure 1 – Example of an Intelligent Intersection in Ingolstadt, Germany



Source: THI-Carissma.

Beyond its role in perception, intelligent infrastructure can serve as a technical supervisory level for L4/L5 systems. It enables system-independent support for safe operation by observing traffic from an external perspective and detecting safety-relevant situations at an early stage. This support is scalable, as a single infrastructure component – for example, at an intersection – can simultaneously support multiple vehicles from different manufacturers. This creates an additional level of safety that makes the operation of highly automated vehicles in public spaces more transparent, robust, and easier to monitor [23].

3.2. Regulation: Status and challenges in Europe

3.2.1. Current status

Legislation governing AVs in the EU is built upon a multi-layered structure that combines EU-wide regulations, international United Nations standards, and national laws within MS. This framework aims to ensure that AVs are safe and can be used across borders, and that they comply with common technical and safety requirements, while preserving MS' sovereignty in terms of traffic rules and conditions of use.

Key EU regulatory framework

At the heart of EU legislation on automated vehicles is a set of type approval and safety regulations that establish minimum requirements for vehicles before they can be sold or operated within the single market.

The General Safety Regulation (EU) 2019/2144 provides the foundational legal basis for the approval of automated and driverless vehicles in the EU [24]. It mandates the integration of Advanced Driver Assistance Systems (ADAS) such as intelligent speed assistance and emergency lane-keeping systems, and it establishes the framework for the future extension to higher levels of automation.

This regulation has applied progressively since July 2022 and is designed to harmonise vehicle safety requirements across all MS.

Commission Implementing Regulation (EU) 2022/1426 supplements the General Safety Regulation by establishing uniform procedures and technical specifications for the type approval of ADS in fully automated vehicles [25]. It thus creates a legal framework for the type approval of Level 4 AVs under EU law. It enables a type-approval procedure for small series (up to 1,500 vehicles per type per year), covering use cases such as robotaxis, hub-to-hub freight services, and automated valet parking.

The EU AI Act (Regulation (EU) 2024/1689), scheduled to apply by August 2026, is another significant regulatory layer [26]. While not specific to vehicles, it classifies ADS as "high-risk AI systems". This classification triggers stringent requirements regarding data quality, robustness, cybersecurity, and human oversight to ensure that AI-based components used in automated driving meet high safety and ethical standards.

International alignment: UNECE/UN regulations

The EU aligns many of its technical requirements for automated driving with international standards developed by the United Nations Economic Commission for Europe (UNECE) under the World Forum for Harmonisation of Vehicle Regulations (WP.29). EU type-approval legislation often incorporates or references these UN regulations.

One of the most important international standards for automated driving is UN Regulation No. 157, which sets uniform provisions concerning Automated Lane Keeping Systems (ALKS). Originally introduced with a speed cap of 60 km/h, subsequent amendments have expanded the allowable operational speed to 130 km/h on motorways and introduced capabilities such as automated lane changes in certain conditions, i. e., critical milestones for achieving Level 3 conditional automation in passenger cars [27].

Another relevant standard is UN Regulation No. 171 (Driver Control Assistance Systems – DCAS), which addresses advanced Level 2 driving assistance systems that still require a human driver to remain engaged but may automate certain maneuvers. It has been transposed into EU law in 2024 (2024/2689) [28].

Both UN Regulations 157 and 171 have been transposed into EU law and are widely used as part of the type-approval basis for advanced ADAS and initial automated driving functions.

Table 2 shows a simplified overview of how automation levels [29] map to current regulatory instruments in the EU.

Table 2 – A simplified overview of how automation levels map to current EU regulations

Automation Level	Status in EU	Primary Regulation
Level 2 (Assisted)	Widely available	UN Regulation 171 / EU transpositions
Level 3 (Conditional)	Approved for motorway use	UN Regulation 157
Level 4 (High)	Limited small series & defined areas	Regulation 2022/1426
Level 5 (Full)	Not yet covered for series production	General Safety Regulation 2019/2144

Source: Produced by the authors.

National implementation in Member States

Even with EU-wide and international standards, the deployment and operation of AVs are further shaped by national legislation, as MS retain authority over traffic rules, operating domains, and permits. For illustration, the current status in selected MS is briefly outlined below.

In Germany the Autonomous Driving Act (2021) [30] and the "Autonome-Fahrzeuge-Genehmigungs- und Betriebs-Verordnung" (AFGBV, 2022) [31] allow Level 4 vehicles to operate in pre-defined public areas without a human driver physically present, provided certain technical supervision and safety criteria are met. German authorities have also aligned domestic rules with international developments such as increasing speeds and automated lane change permissions under ALKS-related regulations.

France published its first road map for the development of automated road public transport in 2018, aimed at building the regulatory framework for the deployment of automated road mobility systems [32]. In France, the deployment regime comes from the Mobility Law (2019) paving the way for legislative and regulatory acts for transport services operated by automated vehicles and systems on public roads. The law was then completed by an ordinance in April 2021 defining the liability regime for the driving of automated vehicles on public roads [33], and an application decree in June 2021 regulating the operation of automated road transport services for passenger transport (respectively November 2024 for freight and logistics transport) [34]. The French framework, articulated with the European type-approval framework defined by (EU) Regulation 2022/1426 (step 1) is based on a self-certification process for service commissioning. France chose a decentralised approach where the service organiser, mainly the public transport authority, is the only entity responsible to decide on service commissioning.

In Italy the Smart Road Decree of 2018 [35] provides the legal basis for testing Level 3 and Level 4 automated vehicles on public roads and drives the nationwide digitalisation of key routes. Italy has not yet enacted a dedicated framework for commercial Level 4 deployment. Through major initiatives such as the JRC Ispra test facility and participation in EU cross-border CCAM corridors, Italy plays an active role in the European strategy to enable large-scale Level 4 operation [36].

Spain is in the final phase of establishing a full regulatory framework for Level 4 automated driving. Since 2022, the updated Traffic Law and DGT Instruction VEH 2022/07 have enabled testing of automated vehicles on public roads under defined permit procedures [35]. A new Royal Decree, expected to take effect in 2026, will provide the first comprehensive legal basis for the permanent operation of fully automated vehicles, moving Spain beyond pilot programs toward commercial deployment [38].

Examples of the current state outside the EU

In the United Kingdom, the Automated Vehicles Act 2024 provides the first comprehensive legal framework for authorising and regulating self-driving vehicles on British roads, shifting liability from human drivers to authorised self-driving entities (ASDEs) and introducing licensing for no-user-in-charge (NUiC) operations [39]. The Act also requires a statutory Statement of Safety Principles, framed to ensure that authorised automated vehicles achieve safety at least equivalent to careful and competent human drivers, to guide vehicle authorisation and ongoing regulation. Under this framework, the UK government is fast-tracking commercial pilot services for Level 4 automated taxi- and shuttle-like vehicles, allowing public booking without a safety driver, with full implementation of the regulatory regime and wider commercial rollout targeted for the second half of 2027 [40].

The United States continues to operate under a dual system where the federal government sets vehicle safety standards while individual states regulate the operation and licensing of AVs. At the federal level, there is still no unified AV statute, but NHTSA has modernized several key Federal

Motor Vehicle Safety Standards to accommodate vehicles without traditional controls such as steering wheels and pedals [41]. State legislation remains highly fragmented: more than 35 states have enacted AV laws, with California, Arizona, Nevada, and Texas permitting full Level 4 driverless operations.

China is moving from pilot programs to national commercialization of AVs. The Ministry of Industry and Information Technology (MIIT) and related agencies have implemented three mandatory standards : GB44495-2024 (cybersecurity), GB 44496-2024 (software updates), and GB 44497-2024 (data recording) to ensure safe and accountable operations [42]. In late 2025, MIIT issued the first permits for two Level 3 automated passenger cars, which are allowed to operate only on designated roads in Chongqing and Beijing [43]. China's robotaxi sector is also expanding rapidly: Baidu's ApolloGo has logged over 240 million kilometers and millions of paid autonomous rides across more than 22 cities, demonstrating both commercial scale and real-world deployment [44].

Forthcoming Global UN Regulation on Automated Driving Systems

A major forthcoming development in international regulation is the Global UN Regulation on Automated Driving Systems [45]. It is expected in 2026. Unlike earlier vehicle-feature-specific standards, this draft regulation aims to provide a comprehensive and harmonised global framework for the assessment and approval of automated driving functions at Levels 3 and 4. It will be a comprehensive regulation that establishes requirements for ADS based on key foundations: Safety Management System (SMS), Credibility of test methods, Safety Case, In-Service Monitoring and Reporting (ISMR), and Data Storage System for Automated Driving (DSSAD). The main features include:

- A performance-based safety goal, requiring automated systems to be at least as safe as a "competent and careful human driver" in mixed traffic.
- Critical functions like longitudinal/lateral control, object detection, and "minimum risk maneuvers", e. g., bringing the car to a safe stop if the system fails or the driver does not take over.
- A multi-pillar assessment approach that combines physical testing, virtual simulation, and analysis of real-world driving data to evaluate system safety.

This harmonised standard will help reduce fragmentation in global regulatory regimes and offer clearer ways for vehicle manufacturers and software developers.

3.2.2. Challenges

Although the EU has a harmonised type approval system for fully automated vehicles, it still faces significant regulatory challenges on the road to widespread deployment. The current legal framework, based on Regulation (EU) 2022/1426, provides the legal basis for the approval of Level 4 AVs, but its practical implementation faces a number of challenges. A limitation of the current EU type approval framework is that, according to the delegated implementing legislation associated with Regulation (EU) 2022/1426, the approval of fully AVs is currently restricted to a small series production, i. e., up to 1,500 vehicles per type per year [46]. This is a bottleneck that prevents the transition from pilot projects to large-scale mass marketing within the single market.

A major challenge concerns the harmonised interpretation and operationalisation of the new legal requirements. Regulation 2022/1426 introduces several novel concepts for type approval, such as safety management systems, validation of ODDs, remote operations, fallback strategies, and cybersecurity obligations. Thus, national approval authorities and industry stakeholders need guidance to apply these consistently. The European Commission's JRC Report "Interpretation of EU Regulation 2022/1426 on the Type Approval of Automated Driving Systems" [47] was published to address this need and to help establish practices across MS for interpreting the Regulation's provisions.

The EU must also bridge the gap between vehicle approval (e. g., type-approval for Level 4 ADS under Regulation 2022/1426) and operational approval (i. e., where, when, and how vehicles are allowed to drive on public roads), since road traffic law remains a national competence. MS define where and how Level 4 vehicles may operate within their territories, leading to different deployment conditions, geographic restrictions, and approval procedures. This fragmentation complicates cross-border automated mobility. In order to coordinate national approaches establishing a new European administrative agency – similar to the European Union Agency for Railways – might be a helpful measure. Its major tasks might include the definition of harmonised criteria for ODDs, standardised safety cases and the mutual recognition of national operational approvals. Additionally, such an agency might coordinate and manage incident and accident data that will result by the deployment of AVs. Based on this data it could play an important role as political consultancy agency.

Attracting more capital for the development and deployment of AVs in Europe is another key challenge. In [48] it is pointed out that in the area of connected and self-driving vehicles in 2024 the Americas attracted $10 billion, Asia $6.6 billion, and Europe only $1.5 billion. Possible reasons for the relatively small investments in Europe might be the still fragmented regulations regarding deployment or the high costs of AVs, questioning a positive business-case for private transport at current time. For example OEMs like BMW and Mercedes-Benz are shifting their AVs focus back from Level 3 to Level 2 [49]. The reasons might be high development and operation costs for AVs connected with limited operating scenarios which lead to a low consumer adoption. For public transport some industry representatives criticise the lack of strategic direction and investments in the EU for AVs compared to Japan and China [50]. To attract more capital initiatives like "European Connected and Autonomous Vehicle Alliance" (ECAVA), large-scale cross-border testbeds with related regulatory sandboxes, or "Important Project of Common European Interest" (IPCEI) allowing Member States to grant substantial state aid that would normally be problematic under EU state aid law, are of great importance. However, such initiatives must have a substantial funding to achieve significant impacts in order to attract more capital.

Finally, another challenge arises from the interaction between ADS regulation and broader EU digital legislation, including the AI Act, the General Data Protection Regulation (GDPR), the Data Act, and the Cybersecurity Act. Automated driving relies heavily on the processing of large amounts of data, the training of AI models, continuous software updates, and remote monitoring. Aligning vehicle-specific safety regulations with EU-wide data and AI frameworks remains legally complex and requires coordinated implementation to avoid conflicting obligations for manufacturers and operators.

3.3. Scenarios

Scenarios are an effective tool for envisioning possible futures and preparing for them. In the context of AVs in the EU, scenario planning enables the exploration of different development paths by providing structured narratives that help anticipate and understand potential impacts, rather than predicting the future.

Three scenarios are considered in this study:

Scenario 1: European Leadership. The EU becomes as a global leader in automated driving technology and policy. It sets benchmarks for innovation, safety, and regulation, guiding the worldwide deployment of AVs.

Scenario 2: Selective Strengths and Dependencies. Europe maintains excellence in selected domains but remains dependent on foreign technologies in critical areas such as AI hardware or data infrastructure.

Scenario 3: External Dependence. The EU is becoming largely dependent on technologies, standards, and regulatory models developed abroad. The use of AVs in Europe is following international developments rather than helping to shape them.

3.3.1. Scenario 1: European Leadership

Overview: By the mid of the 2030s, the EU has emerged as a global leader in the development, regulation, and deployment of AVs. A harmonised legal framework ensures interoperability across MS, while strong Public–Private Partnerships (PPP) drive innovation in AI, SDVs, and Intelligent Infrastructure. The EU's proactive approach not only fosters technological excellence but also establishes international standards for safety, ethics, and data governance in automated mobility.

Technological baseline: In this scenario, Europe achieves a high level of technological maturity across all major AV domains. AI development advances through both modular and end-to-end architectures supported by large European datasets. SDV architectures are widely used and enable continuous updates, fleet learning, and harmonised interfaces. Intelligent Infrastructure expands consistently throughout the EU, including high-quality digital twins, high-fidelity roadside sensing, and dense network connectivity. These technologies evolve in a coordinated and interoperable manner, enabling reliable, scalable automated driving across MS.

Regulatory and policy alignment: Legislation at EU and national level will be consolidated into a harmonised legal framework that supports cross-border interoperability and uniform safety standards. Type approval and area of operation authorisation procedures will be streamlined, and MS will interpret the key requirements in a uniform manner. Common technical specifications, common test protocols and coordinated approaches to data management will minimise legal uncertainty. The regulatory environment will be predictable, stable and conducive to large-scale deployment, enabling Europe to speak with one voice internationally and influence the setting of global standards.

R&D ecosystem and impact: Europe is developing a strong research ecosystem. Universities, research institutions and industry collaborate through well-established networks, shared test facilities and shared data. European players excel in core technologies such as AI perception, planning, safety validation and simulation-driven development. Close links between research institutions and industry accelerate the transfer of innovations into practice. Europe's innovation cycle is globally competitive, and European intellectual property plays a central role in the automated mobility value chain.

Economic and social impact: The AV sector makes a significant contribution to economic growth in Europe by strengthening the automotive industry, promoting high-quality supply chains and supporting new service models in the areas of mobility, logistics and infrastructure. Europe is becoming an exporter of AV technologies and generating added value in the areas of hardware, software and services. Employment is shifting towards highly skilled jobs in engineering, AI research, cybersecurity, system integration and Mobility-as-a-Service (MaaS). While some traditional professions related to driving vehicles are becoming less important, the change is being accompanied by training and retraining programmes, so that the overall impact on the labour market is stable or positive. Public confidence is increasing due to transparent safety practices and reliable service delivery.

Impact on public transport: Automated mobility is being integrated into the public transport system as a complementary pillar. Autonomous shuttles, buses and demand-responsive fleets are improving coverage in rural and peri-urban areas and improving first and last mile connections. Public transport authorities are working closely with operators and manufacturers, enabling harmonised fleet management and shared data platforms. The overall result is a more efficient, accessible and sustainable mobility ecosystem in which AVs do not replace public transport, but rather strengthen it.

3.3.2. Scenario 2: Selective Strengths and Dependencies

Overview: In this scenario, the EU retains strong capabilities in specific domains of automated driving, such as safety validation, but remains dependent on global partners for critical technologies like advanced AI chips, large-scale model training, and proprietary software stacks. Europe continues to play a relevant but not dominant role in the global automated mobility ecosystem.

Technological baseline: Europe performs strongly in some areas of technology, but remains dependent on international manufacturers in others. Modular and hybrid AI architectures dominate, reflecting Europe's strengths in safety-critical engineering and validation. Progress in end-to-end learning is slower due to limited access to computing resources, proprietary data sets and specialised hardware. SDV capabilities exist but vary by manufacturer, resulting in heterogeneous upgrade options and interface standards. Intelligent Infrastructure is developing unevenly, with some regions operating advanced digital systems while others continue to rely on older configurations. Europe supplies key components but does not control the entire technology stack.

Regulatory and policy alignment: Regulation in MS shows some convergence. Some national authorities work closely together and commit to compatible interpretations of key requirements, while others continue to apply different approval procedures. As a result, cross-border operation is possible but not seamless, requiring bilateral agreements or technical adaptations. Safety standards and data management frameworks are based on common principles but differ in detail. Overall, Europe is pursuing a regulatory approach that supports the introduction of AVs, but the lack of full harmonisation leads to legal and administrative complications.

R&D ecosystem and impact: The European R&D ecosystem remains strong in selected areas such as automotive engineering, safety verification, and intelligent transport systems, but faces structural dependencies in large-scale AI training and certain sensor technologies, e. g., LIDAR. Joint research projects continue to produce valuable innovations, but the fragmentation of data sets, testing environments and specialised resources limits the scalability of breakthroughs. Europe influences global research trends in certain niches, while relying on technology transfer and partnerships in other areas.

Economic and social impact: Economically speaking, Europe retains a competitive position in several segments of the AV value chain, but relies on imported technologies for high-performance computers, AI platforms, and proprietary software stacks. This leads to mixed results for the industry: some sectors are thriving, while others suffer from cost pressures and strategic vulnerability. The impact on employment is similarly mixed. Highly skilled jobs are being created in engineering, systems integration and transport, but innovation jobs in the areas of large AI models or advanced chip design continue to be concentrated outside Europe. Social responses vary by region, with AVs acceptance higher in areas benefiting from early adoption and acceptance lower where adoption is still limited.

Impact on public transport: Public transport systems are selectively integrating AV technologies. Leading cities and regions are deploying automated shuttles, buses or on-demand services where local capacity and infrastructure are sufficiently developed. Other regions are struggling to introduce AV-supported services due to costs, infrastructure deficits or differing regulations. The result is a heterogeneous mobility landscape: AVs improve connectivity in certain areas, while others continue to rely primarily on conventional public transport. Interoperability between AV fleets and public transport platforms varies accordingly.

3.3.3. Scenario 3: External Dependence

Overview: In this scenario, the EU becomes largely dependent on international developments in the field of AVs. Europe lacks leadership in critical areas of AI, SDVs and smart infrastructure and is primarily reliant on imported technologies and foreign regulatory models. Although AVs are being deployed in the EU, Europe plays only a reactive role, following standards, platforms and innovations defined or developed elsewhere. Regulatory frameworks and public perception evolve in response to international trends rather than as a result of European strategic planning.

Technological baseline: The introduction of AV technologies in Europe is primarily driven by technologies developed abroad. End-to-end learning architectures, large AI models, computing platforms, SDV operating systems and digital infrastructure solutions are largely imported. European industry tends to focus on integration, compliance and adaptation to local conditions rather than on its own innovations. The strategic direction of the technology is determined by external players. Intelligent Infrastructure is developing through manufacturer-specific systems, which limits interoperability and long-term technological sovereignty.

Regulatory and policy alignment: The regulatory framework in Europe remains diverse, reflecting national preferences and the influence of external technology providers. Some AV systems enter the market via proprietary approval pathways dominated by global companies. MS adopt heterogeneous operating rules, safety assessments and data requirements based on imported technologies. Cross-border AV operations are rare, and Europe has limited influence on global standard setting. Often, foreign regulatory models are adapted rather than actively shaped.

R&D ecosystem and impact: The domestic research landscape is comparatively weak in fundamental AI and AV technologies. European institutions continue to have expertise in safety validation, transport systems and legislative expertise, but lack the resources to drive cutting-edge innovation in perception, planning or large-scale AI. Limited access to computing resources and proprietary training datasets constrains research performance. European contributions tend to focus on adaptation, testing and specialised niche technologies rather than breakthroughs at the system level.

Economic and social impact: The European economy in the field of automated mobility is becoming heavily dependent on foreign technology providers. Value creation is concentrated on lower-margin activities such as integration, fleet operation, maintenance and regulatory compliance, rather than on high-value hardware and software development. Highly skilled jobs in core areas of AI, chip design and advanced vehicle software are declining, while operational and maintenance-oriented jobs are growing moderately. Issues of data sovereignty, vendor dependency and resilience are becoming key social issues. Public confidence varies, with some groups sceptical of foreign-controlled systems.

Impact on public transport: Public transport authorities are dependent on foreign AV platforms, which are often tied to proprietary ecosystems. Deployment is predominantly via turnkey solutions with limited opportunities for local customisation. Interoperability with existing public transport systems is limited, and service optimisation is heavily dependent on manufacturer tools. Although AVs can continue to improve mobility in selected contexts, public actors have limited strategic control over technological decisions, data flows and long-term system design.

4. Evaluation of scenarios and Conclusions

To evaluate the scenarios a set of semi-structured interviews was conducted with a selected group of stakeholders, including industry experts, researchers, and representatives from relevant organisations. An overview of the Interview Partners (IP) is provided in Annex 1.

The interviews reveal a broad consensus that Scenario 2, in which Europe maintains selective technological and regulatory leadership while remaining dependent on global partners for key components, is the most plausible outcome for AV deployment in Europe. A clear majority of interview partners explicitly identify Scenario 2 as the most likely scenario (IP2, IP3, IP4, IP6, IP7, IP9, IP10, IP11, IP12). Several others position their assessment between Scenarios 2 and 3, warning that without stronger strategic intervention Europe risks gradually falling behind despite regulatory strengths (IP5, IP8). One expert (IP1) places Europe between Scenarios 1 and 2, emphasizing Europe's strong role in shaping global safety, regulatory, and data governance standards, while expressing reservations about full technological leadership. IP12 broadly aligns with Scenario 2 but stresses that, given Europe's single market, active startup ecosystem, and ongoing policy actions, a move towards Scenario 1 remains possible if regulatory leadership, public funding, and industry engagement are effectively combined.

Across interviews, Europe's strengths are consistently located in safety engineering, verification and validation, regulatory frameworks, and system integration, while limitations are seen with regard to large-scale AI systems (IP2, IP3, IP4, IP5, IP6, IP7, IP10, IP11). Europe is widely described as a global champion in regulation (IP1, IP3, IP12), though IP12 also cautions that regulation can act as a barrier to immature technologies and therefore needs to balance safety with timely deployment, for example through cross-border testbeds.

Particularly IP6 expects AV deployment in Europe to focus on practical and controlled applications, such as first-/last-mile people movers and structured logistics use cases (e. g. hub-to-hub operations), where Europe can build on regulatory maturity and operational expertise. At the same time, multiple interview partners note that Europe is unlikely to match the scale of the US or China in highly data-driven, end-to-end AV systems or robotaxi platforms (IP3, IP6, IP7, IP10).

Regulatory and legal considerations

Regulations, such as EU Regulation 2022/1426 and UN-R157, establish a harmonised EU-wide legal framework for AVs, which experts (IP1, IP2, IP3, IP4, IP6, IP7, IP9, IP10, IP11, IP12) recognize as a strong foundation for legal certainty and public trust. Harmonisation allows mutual recognition of type approvals and alignment with ISO safety standards. At the same time, national authorities are seen as retaining an important role in approving concrete operational domains and use cases, particularly for specialized or locally embedded applications (IP3, IP6, IP9), e. g., for specialized vehicles like class L goods movers. Since deployment and use and operation of AVs is not part of the internal EU market and therefore essentially regulated at a national level, IP9 highlights that a system-oriented approach is needed in which a AV is recognized as a new road user to whom all other road users must relate. So, a harmonized EU-wide legal framework for the market introduction of AVs should go hand in hand with EU-wide aligned national regulations accommodating the use of (type-approved) AVs in existing functional contexts and provide legal clarity for all road users. Otherwise, AVs may be legally placed on the market but face practical restrictions on their use due to insufficient national legal frameworks.

While there is general agreement on the benefits of harmonisation, experts express differing views regarding flexibility in legislation. Some experts caution that excessive legislative flexibility could undermine safety, consistency, and trust (IP1, IP3), whereas others argue that targeted flexibility, for example through regulatory sandboxes or phased approvals, can enable controlled experimentation and learning without compromising safety (IP4, IP7, IP11). The interviews therefore suggest no uniform demand for legislative flexibility.

Several interview partners also raise the issue of protecting strategically relevant aspects of AV deployment, particularly where AVs intersect with safety-critical infrastructure and public services. While no interview partner explicitly calls for comprehensive protectionism, concerns are expressed about over-reliance on non-European actors in critical system components and governance structures (IP5, IP8). So, selective safeguards could become a regulatory consideration.

Citations from the interviews:

"Europe will achieve significance in Automated Driving not through more regulation, but through smarter regulation." (IP5)

"*Existing* traffic regulations are developed for and around people interacting in traffic, including pedestrians, cyclists, traffic enforcers, and road workers and *not* for (automated) vehicles." (IP9)

Technological capabilities and dependencies

Experts consistently highlight Europe's strength in safety assessment, verification and validation (V&V), and regulatory compliance, which positions it as a credible leader in selective domains (IP1, IP2, IP3, IP4, IP6, IP7, IP12). This implies that Europe must remain actively involved in the development of core automated driving technologies. This is not only a matter of industrial competitiveness but a prerequisite for credible assessment, robust V&V, and effective regulatory design. Regulatory leadership in complex, AI-driven mobility systems require hands-on engineering competence and continuous engagement at the technological frontier in order to understand, evaluate, and challenge system architectures. Without such involvement, Europe risks becoming a rule-maker without sufficient technological grounding, weakening its ability to assess external solutions, shape global standards, and legislate with authority (IP5). Active participation in technology development is therefore essential for strategic autonomy, regulatory sovereignty, and long-term resilience in automated mobility. However, some interview partners also point to Europe's limitations in large-scale AI development environments, including access to massive datasets, compute-intensive development, and globally scaled AV platforms (IP2, IP3, IP5, IP6, IP7, IP10). Consequently, European AV strategies are expected to focus on selective leadership in areas where regulatory and operational expertise create competitive advantage, while relying on global partners for AI compute and other components (Scenario 2).

Citations from the interviews:

"Safety before speed." (IP3)

"Technological development capacity forms an essential pillar of Europe's strategic autonomy. Regulatory leadership in complex, AI-driven mobility systems cannot be exercised independently of hands-on engineering expertise and continuous participation at the technological frontier." (IP5)

R&D approaches and public funding

A hybrid research model combining Centers of Excellence (CoE) with distributed networks of research institutions is generally favored (IP1, IP4, IP5, IP7, IP9, IP11, IP12), though IP3 and IP6 express caution regarding coordination challenges. IP12 explicitly emphasizes that the need for CoE depends on the Technology Readiness Level (TRL): for high TRL technologies, fewer but larger CoE-driven projects may be appropriate, whereas lower TRL innovation benefits from broader, distributed research. This approach is mostly seen as balancing concentration of expertise with broad participation and knowledge exchange. Targeted public funding and PPP are seen as essential for deployment-oriented research to tackle the complexity of development, verification, validation, type approval and certification of automated mobility (IP1, IP4, IP7, IP12), though IP12 also highlights timing challenges in public funding relative to rapid technological change.

Citation from the interviews:

"The need for Centers of Excellence depends on the Technology Readiness Level. At higher TRLs Centers of Excellence might be useful." (IP12)

Collaboration and structural barriers

Structural and regulatory barriers to collaboration between research institutions and industry are perceived as moderate but manageable. Challenges include differing incentives, IP management, administrative complexity, and procurement rules (IP7), whereas other experts note that strong pre-competitive research frameworks and selective PPPs can facilitate cooperation without compromising innovation (IP5, IP6).

Implications for scenario realization

Overall, the interviews suggest that Europe's path might be characterized by:

- Selective technological leadership, particularly in safety, verification and validation, integration, and regulatory compliance.
- Continued dependence on international partners for some critical AV components, e. g., AI hardware and end-to-end AI solutions.
- Strong, harmonized regulatory frameworks with targeted flexibility for pilot projects and controlled experimentation.
- Strategic R&D and funding focused on applications with high impact, rather than pushing for full technological autonomy.

5. Policy options and their assessment

This chapter examines how different policy options could shape the future deployment of AVs in the EU. The assessment builds directly on the three scenarios developed in Chapter 3, i.e., European Leadership, Selective Strengths and Dependencies, and External Dependence.

Rather than predicting outcomes, this chapter explores the consequences of each policy option: if a particular policy path were chosen, then its implications would differ across the three scenarios. The analysis covers two key policy areas:

- Legislation and deployment frameworks, which determine how AVs are regulated and approved in the EU and
- Support for R&D, which defines how innovation capacity and technological sovereignty are fostered.

5.1. Policy Area 1: Legislation and deployment

5.1.1. Policy Option 1: A harmonised European framework with coordinated national legislation for AV deployment

This policy option preserves a balance between national flexibility and EU-level coordination. It builds on the EU's existing approach, whereby common EU rules, such as the General Safety Regulation (EU) 2019/2144 and the Commission Implementing Regulation (EU) 2022/1426 set harmonised safety and approval requirements, while MS retain the flexibility to determine the operational conditions for automated vehicles themselves. It also fits in with the planned Global UN Regulation on ADS. Under this option, the EU would continue to provide overarching rules and guidelines, while national authorities would adapt the specific operating rules to their respective infrastructure, traffic conditions and mobility needs.

In the European Leadership scenario this policy option allows MS to tailor rules to local conditions while still contributing to a coherent European strategy. National experimentation can accelerate innovation, enabling frontrunner countries to pioneer advanced deployments that later feed into EU-wide standards. Because Europe is technologically strong in this scenario, flexibility would support faster learning and the broader adoption of effective approaches. *In this scenario, coordinated national approaches complement Europe's leadership by combining local innovation with guidance and alignment at the EU level.*

In the Selective Strengths and Dependencies scenario the balance between national flexibility and EU coordination becomes particularly valuable. National authorities can support deployments that align with regional strengths, such as controlled environments or public-transport-focused solutions, while the EU ensures compatibility and avoids market fragmentation. However, the diversity of national approaches might lead to uneven progress if frontrunner states move ahead while others lag behind. Effective minimum standards and coordination mechanisms would therefore be essential to prevent divergence that could harm the European AV market. ***In this scenario, the policy option supports EU-wide consistency in the introduction of AVs, but EU coordination is needed to ensure that different national speeds of progress do not lead to market fragmentation. Support is necessary to share and extend best practices among MS.***

In the External Dependence scenario, coordinated national legislation under EU guidelines helps maintain a minimum level of consistency across MS even as Europe relies heavily on foreign AV technologies, platforms, and software stacks. National flexibility allows countries to adopt and integrate external systems at different paces, but this also increases the risk of uneven regulatory implementation and varying levels of dependency across the EU. The role of EU-level coordination therefore becomes to maintain alignment, ensuring that national strategies remain consistent with high safety standards and interoperability. *In this scenario, the policy option provides essential baseline alignment but does little to reduce external dependencies, and it may widen differences between MS.*

Note from the authors:

In the authors' view, the current dual approach, i.e., combining harmonized European type-approval with national-level flexibility for operational approval, effectively addresses the diverse traffic complexities found across Europe.

5.1.2. Policy Option 2: A protectionist market approach

A protectionist market approach treats selected elements of AV technology and deployment as part of critical infrastructure. This would require first identifying which components are strategically critical for safe and reliable AV operation, e. g., vehicle software architectures, safety-critical control systems, data flows, connectivity with infrastructure, operational platforms, etc. The next step would be the application of targeted measures to protect or privilege European capabilities in these areas. Such measures could include market access restrictions, preferential procurement, investment screening, or limits on foreign control in safety-relevant systems. The objective is not full technological autarky, but the reduction of strategic dependencies in domains that are essential for public safety, resilience, and long-term industrial sovereignty. For example, OTA Updates in SDVs bring along risks like remote control of vehicles as shown in [49].

In the European Leadership scenario targeted protection would mainly serve as a stabilising instrument by safeguarding domestic capabilities in critical AV technologies. However, overly broad protectionist measures could slow international collaboration and reduce Europe's influence on global standards. *In this scenario, a protectionist approach can consolidate leadership, provided it remains selective and proportionate.*

In the Selective Strengths and Dependencies scenario a protectionist market approach could play a more constructive role than in the other scenarios. By shielding strategically critical AV technologies and deployment domains from immediate external competition, protectionist measures could create protected spaces for capability building, allowing European actors to invest, scale, and gradually catch up in selected key technologies. In combination with targeted public support and clear regulatory priorities, such an approach could help transform existing strengths in safety, integration, and regulation into broader technological competence over time. At the same time, the effectiveness of this strategy would depend on its scope and duration. If protection extends beyond clearly defined critical areas or is not accompanied by strong innovation incentives, it could slow development, increase costs, and reduce the ability to benefit from technological progress occurring outside the EU. The approach therefore carries both an opportunity for strategic consolidation and a risk of inefficiency. ***In this scenario, a protectionist approach can support technological catch-up in critical domains, if it is targeted and closely aligned with innovation and deployment objectives.***

In the External Dependence scenario a protectionist market approach would be difficult to implement effectively. Without a strong domestic technological base, restricting external providers could delay AV deployment, reduce competition, and weaken market attractiveness without meaningfully rebuilding internal capabilities. Protectionist measures might discourage foreign investment, further reinforcing Europe's dependent position. *In this scenario, a protectionist approach risks increasing isolation without significantly reducing structural dependence.*

Note from the authors:

In the author's view, if autonomous vehicles are considered as part of the critical infrastructure, pursuing a development and market approach focused on strategic protection is, at least in part, justified.

5.2. Policy Area 2: EU support for research and development

5.2.1. Policy Option 3: Distributed research with coordinated funding

This policy option builds on the existing EU model, in which research institutions across MS are supported through competitive funding mechanisms such as Horizon Europe. It fosters collaboration, knowledge exchange, and cross-border networks, enabling distributed research efforts while aligning projects with EU-level priorities in AV technologies.

In the European Leadership scenario a distributed research landscape fits well with the scenario's emphasis on broad European technological capabilities. It enables MS to strengthen their own research ecosystems while contributing to a shared knowledge base. Coordinated funding mechanisms ensure alignment on strategic priorities like AI architectures, validation methodologies, SDV platforms, and intelligent infrastructures, while maintaining diversity in innovation. However, distributed efforts require strong coordination to avoid duplication or fragmentation. If successfully aligned, this model can support leadership by mobilizing a wide pool of expertise across Europe. *In this scenario, the policy option enhances Europe's leadership by expanding the collective research capacity, with coordinated funding ensuring focus and alignment.*

In the Selective Strengths and Dependencies scenario a distributed research approach supports the idea of selective excellence. MS can focus on national strengths, while still contributing to European strategic goals. Coordinated funding helps mitigate dependencies by fostering collaborative networks, but strong and focused coordination is required. The model supports knowledge exchange but may struggle to scale in resource-intensive domains if efforts remain too fragmented. ***In this scenario, the policy option contributes to strengthening niche capabilities but might have limited impact on overcoming structural dependencies on non-European AV technology providers.***

In the External Dependence scenario distributed research may help maintain basic competencies but lacks the critical mass required to decrease dependence on non-European AV technologies. Fragmented efforts, even if coordinated through EU funding schemes, may be insufficient to compete with consolidated international research ecosystems. Without central hubs capable of addressing large-scale AI training or system integration, Europe risks deepening its dependency. Still, this option helps ensure that MS do not fall behind entirely. *In this scenario, the policy option maintains minimal research capacity but does little to combat dependencies on non-European AV technology providers.*

Note from the authors:

In the author's view, a distributed research approach with coordinated funding for AVs fosters collaboration and knowledge exchange between MS but might be insufficient on its own to achieve the innovation speed necessary for global competition in this sector.

5.2.2. Policy Option 4: Centres of Excellence supporting distributed networks (hybrid model)

This policy option combines a limited number of central CoE with a distributed network of research nodes, enabling focused R&D for AV technology while maintaining broad participation, knowledge exchange, and access to shared infrastructure across Europe.

In the European Leadership scenario the hybrid model offers the advantages of both scale and inclusiveness. CoE provide critical mass for high-end research, while distributed nodes ensure broad participation and diversity of innovation. This creates a resilient ecosystem capable of addressing complex AV challenges across AI, SDV platforms, and intelligent infrastructure. Strong coordination mechanisms amplify Europe's ability to shape international standards and maintain technological primacy. *In this scenario, the policy option delivers a balanced and robust research ecosystem, supporting leadership on AV technology.*

In the Selective Strengths and Dependencies scenario a hybrid model aligns well with selective leadership, allowing high-capacity hubs to drive strategic topics while distributed nodes specialize in complementary areas. This configuration helps mitigate dependency risks more effectively than a fully distributed model, although it still requires significant investment in coordination and infrastructure. It also ensures that MS with different industrial strengths can contribute meaningfully. ***In this scenario, the policy option supports well-coordinated development of key areas in AV technology while enabling partial reduction of dependencies on non-European AV technology providers.***

In the External Dependence scenario the hybrid model provides flexibility but requires strong governance and funding, which may be difficult under dependency pressures. Central hubs may rely heavily on external technology providers, while distributed nodes may lack resources to meaningfully contribute. Nevertheless, the model maintains at least a baseline of research capability. *In this scenario, the policy option offers modest resilience but cannot counteract Europe's broader dependencies on non-European AV technology providers.*

Note from the authors:

In the author's view, combining concentrated expertise in selected CoE with broad participation from all MS represents an effective long-term approach to strengthening Europe's position in the field of AVs. However, this must be based on prior identification of the key technological competencies required for European sovereignty in order to quickly achieve international competitiveness.

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Annex 1: List of experts interviewed for the study

The following list presents the Interview Partners (IP) for this study.

Interview Partner 1: Prof. Klaus Kompaß; Freelancer KKo4Safety

Interview Partner 2: Richard Bishop; Principal at Bishop Consulting

Interview Partner 3: Frank Schneider; Speaker in the Vehicle & Mobility Department, TÜV Association

Interview Partner 4: Christian Merkt, CCAM Association Chairman

Interview Partner 5: Prefers not to be named; Many years of experience in the automotive industry, recently in China

Interview Partner 6: Udo Steininger; CEO and Co-Founder TESACO GmbH

Interview Partner 7: Prefers not to be named; Many years of experience in AV-related research projects

Interview Partner 8: Prof. Sergio Matteo Savaresi; University "Politecnico di Milano"

Interview Partner 9: Antoine de Kort MSc; Principal advisor for Automated Transport Policy on behalf of the Netherlands Ministry of Infrastructure and Water Management, and chair of the European Forum for Automated Transport (EFAT)

Interview Partner 10: Prof. Angelo Bonfitto; University "Politecnico di Torino"

Interview Partner 11: Stephane Dreher PhD; Head of CCAM, ERTICO – ITS Europe

Interview Partner 12: Maria Cristina Galassi PhD; European Commission DG GROW

Annex 2: Scenario description

The following three scenarios are considered in the study. These hypothetical scenarios should be seen as possible extreme situations against which stress testing the policy options being proposed in the study.

Scenario 1: European Leadership

The European Union (EU) emerges as a global leader in automated driving technology and policy. It sets benchmarks for innovation, safety, and regulation, guiding the worldwide deployment of Autonomous Vehicles (AVs, i.e., Automation Level 4 or 5).

By the mid-2030s, the EU has emerged as a global leader in the development, regulation, and deployment of AVs. A coherent and harmonized legal framework ensures interoperability across EU Member States, while strong public–private partnerships drive innovation in Artificial Intelligence (AI), Software Defined Vehicles (SDVs), and intelligent transport infrastructure. The EU's proactive approach not only fosters technological excellence but also establishes international standards for safety, ethics, and data governance in automated mobility.

Scenario 2: Selective Strengths and Dependencies

The EU retains core competencies in several strategic areas of automated driving but remains dependent on international actors for other crucial components. While Europe contributes significantly, the overall ecosystem requires collaboration beyond its borders to manage the full complexity of deployment.

In this scenario, the EU retains strong capabilities in specific domains of automated driving, such as safety validation or intelligent infrastructure, but remains dependent on global partners for critical technologies like advanced AI chips, large-scale model training, and proprietary software stacks.

Scenario 3: External Dependence

The EU becomes largely reliant on technologies, standards, and regulatory models developed abroad. AV deployment in Europe follows international developments rather than shaping them.

In this scenario, the European Union becomes largely dependent on international developments in AVs. Europe lacks leadership in critical domains of AI, SDVs, and intelligent infrastructure, relying primarily on imported technologies and foreign regulatory models. Deployment of AVs occurs in the EU, but Europe plays a reactive role, following standards, platforms, and innovations defined elsewhere. Regulatory frameworks and public perception evolve in response to international trends rather than European strategic planning.

Annex 3: Interview questions

Question 1 (Citation Consent):
Do you agree to be cited by name in the report, or would you prefer your contribution to remain anonymous?

Question 2 (Scenario Likelihood):
Having presented the three future scenarios for the deployment of Automated Vehicles, which scenario do you consider most likely to occur in the European context, and why?

Question 3 (Harmonized EU Legislation):
On a scale from 1 (do not agree) to 5 (fully agree), to what extent do you agree that establishing a harmonized EU legislative framework for Automated Vehicles would be more effective than maintaining largely independent national approaches? Please explain your reasoning, including potential benefits or drawbacks.

Question 4 (EU-Wide Homologation Process):
On a scale from 1 (do not agree) to 5 (fully agree), to what extent do you agree that a dedicated EU-wide homologation framework (either general or differentiated by vehicle type and level of automation) is necessary to provide legal clarity and ensure public trust for large-scale AV deployment? Please provide any comments.

Question 5 (Legislative Flexibility):
On a scale from 1 (do not agree) to 5 (fully agree), to what extent do you agree that EU legislation for Automated Vehicles should prioritize flexibility to adapt to different future scenarios (from European technological leadership to external dependence), even if this may reduce legal certainty or slow initial deployment? Please explain your reasoning.

Question 6 (Preferred R&D Approach):
On a scale from 1 (do not agree) to 5 (fully agree), to what extent do you agree that a hybrid R&D model, combining a few European Centres of Excellence with a distributed network of research institutions, offers the most effective way to secure technological sovereignty, foster innovation, and achieve high-impact outcomes in Automated Vehicle technologies? Please explain your reasoning, and if relevant, comment on the advantages or risks compared to purely distributed or purely concentrated approaches.

Question 7 (R&D Priorities):
On a scale from 1 (do not agree) to 5 (fully agree), to what extent do you agree that EU funding instruments and public–private partnerships should be adapted to better align research priorities in AI, software-defined vehicles, and intelligent infrastructure with the EU's legislative and industrial goals for Automated Vehicles? Please provide any suggestions or examples.

Question 8 (Collaboration Obstacles):
On a scale from 1 (do not agree) to 5 (fully agree), to what extent do you agree that collaboration between research institutions and industry actors is currently hindered by structural or regulatory obstacles? Please explain with examples if possible.

Question 9 (Individual Question):
This is an individual questions for each interview partner, depending on their background and current position.

Annex 4: Aggregated results by interview question

This Annex complements Chapter 4 by providing a brief aggregation of the responses given by the IPs to the interview questions.

Answers to Question 1 (Citation Consent)
10 out of 12 IPs agreed for their name to appear in the list of experts consulted for the elaboration of the study.

Answers Question 2 (Scenario Likelihood)
Mean: Scenario 1.9; Median: Scenario 2.

Answers to Question 3 (Harmonized EU Legislation)
Mean: Median: 4.8; Median: 5.

Answers to Question 4 (EU-Wide Homologation Process)
Mean: 4.7; Median: 5;

Answers to Question 5 (Legislative Flexibility)
Mean: 3.1; Median: 3.

Answers to Question 6 (Preferred R&D Approach)
Mean: 3.1; Median: 3.5.

Answers to Question 7 (R&D Priorities)
Mean: 4.3; Median: 5.

Question 8 (Collaboration Obstacles)
Mean: 2.8; Median: 3.

Annex 5: Acronyms

ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving Systems
AFGBV	Autonome-Fahrzeuge-Genehmigungs- und Betriebs-Verordnung
AI	Artificial Intelligence
ALKS	Automated Lane Keeping Systems
ASDE	Authorised Self-Driving Entities
AV	Automated Vehicle
CCAM	Cooperative, Connected and Automated Mobility
C-ITS	Cooperative Intelligent Transport Systems
DCAS	Driver Control Assistance Systems
DSSAD	Data Storage System for Automated Driving
EU	European Union
GDPR	General Data Protection Regulation
IP	Interview Partners
ITS	Intelligent Transport Systems
ISMR	In-Service Monitoring and Reporting
MaaS	Mobility-as-a-Service
MIIT	Ministry of Industry and Information Technology
MS	Member State
NUiC	No-User-in-Charge
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
OTA	Over-The-Air
PPP	Public-Private Partnerships
R&D	Research and Development
SDV	Software-Defined Vehicle
SMS	Safety Management System

SOTIF	Safety of the Intended Functionality
V&V	Verification and Validation
UNECE	United Nations Economic Commission for Europe

This study examines the future deployment of Automated Vehicles in the European Union through an analysis combining technological assessment, scenario development, and policy evaluation. Building on recent advances in Artificial Intelligence, Software-Defined Vehicles, and Intelligent Infrastructure, the study develops three scenarios – European Leadership, Selective Strengths and Dependencies, and External Dependence – to explore how Europe's regulatory and industrial position might evolve. These scenarios serve as a framework for assessing policy options related to legislation, deployment, and EU support for research and development.

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