№ 5(46) 2025
НАУКА І ТЕХНІКА СЬОГОДНІ
серії: право, економіка, педагогіка, техніка, фізико-математичні науки

СЕРІЯ «Техніка»

UDC 629.33:004.8

https://doi.org/10.52058/2786-6025-2025-5(46)-1159-1198

Artyukh Oleksandr Mykolayovych PhD in Technical Science, Associate Professor at the Faculty of Transport, Department of Automobiles, Heat Engines and Hybrid Power Plants, National University «Zaporizhzhia Polytechnic», Zaporizhzhia, tel.: +38(061) 764–26–47, https://orcid.org/0000–0002–5043–7038

Ruban Dmytro Petrovych Doctor of Technical Sciences, Professor, Department of Automobiles and Tractors Lviv National University of Environmental Management, Dublyany, https://orcid.org/0000-0002-0671-3226

Tarasenko Oleksandr Vitaliyovych Senior lecturer, Department of Transport Technologies, National University «Zaporizhzhia Polytechnic», Zaporizhzhia, tel.: +38(061) 7698-560, https://orcid.org/0000-0001-7882-5481

Petriuk Yurii Ivanovych Postgraduate, Department of Automobiles, Heat Engines and Hybrid Power Plants, National University «Zaporizhzhia Polytechnic», Zaporizhzhia, tel.: +38 (099) 707-97-06, https://orcid.org/0009-0003-4543-1744

Ruban Hanna Yakivna Lecturer, Cherkasy State Business-College, Cherkasy, tel.: +38 (050) 732–20–88, https://orcid.org/0000-0002-8702-8430

UNMANNED TRANSPORT. MODERN TECHNOLOGIES, CHALLENGES, AND PROSPECTS

Abstract. The article provides an in-depth review of the current stage of unmanned transport development, synthesizing information on technological innovations, legislative initiatives, overcome and ongoing challenges, and forecasting future directions of its evolution in the context of global trends and prior research. To achieve this goal, the study focuses on analyzing key changes that occurred specifically between 2020 and 2025, addressing fundamental questions regarding progress and obstacles on the path to autonomous mobility.

Regarding the first key question – **new technologies that have emerged or undergone significant development in recent years** – notable progress has been

made in enhancing sensor systems and data processing algorithms. Between 2020 and 2025, improvements were observed not only in the performance of existing sensors, such as LiDAR (Light Detection and Ranging), radars, and cameras (including higher resolution, range, and interference resistance), but also in their cost reduction, bringing the technology closer to the mass market.

A significant trend has been the advancement of sensor fusion technologies, which integrate data from various sensor types to create a more comprehensive, accurate, and reliable picture of the surrounding environment. Concurrently, a leap in artificial intelligence algorithms, particularly deep learning, has significantly improved object recognition (pedestrians, vehicles, road signs), behavior prediction, and decision-making in complex traffic scenarios.

The development of V2X (Vehicle-to-Everything) communication technologies has also gained momentum, enabling vehicle-to-vehicle and vehicle-to-infrastructure interactions, which are critical for enhancing safety and efficiency, especially in dense traffic conditions. Additionally, advancements in high-definition (HD) maps, powerful computing platforms capable of real-time processing of vast data volumes, and widespread use of simulation environments for virtual testing and validation of control algorithms have played a significant role.

The second critical question concerns **the dynamics of legislative changes**. The 2020–2025 period marked a turning point, shifting from predominantly experimental regulation to more systematic approaches. Many countries, including EU member states, the USA, China, and Japan, actively developed and implemented new laws and standards related to testing unmanned vehicles on public roads, their certification, and safety requirements.

Notable were the initial efforts to regulate commercial operations, particularly for robotaxi services and autonomous freight transport in specific geographic zones or designated routes. At the international level, the United Nations Economic Commission for Europe (UNECE) intensified efforts to harmonize technical regulations, particularly regarding Automated Lane Keeping Systems (ALKS) and other automated driving functions. However, despite significant progress, the legislative framework remains fragmented. Issues such as legal liability in accidents involving highly automated vehicles, cybersecurity standards, data protection, and the normative establishment of ethical principles for AI operation require further thorough development and international coordination.

The third research question focuses on **challenges that have been overcome and those that remain relevant**. Over the past five years, developers have made significant strides in improving the reliability of perception systems in complex conditions, though ensuring flawless operation in extreme weather (heavy rain, snowfall, fog) or poor lighting remains a major technological barrier.

Considerable attention has been devoted to cybersecurity, with the development of protocols to protect against hacking and unauthorized access, though this threat remains persistent and demands ongoing vigilance. Public discourse on ethical aspects, particularly programming vehicle behavior in unavoidable crash scenarios, has intensified, prompting initial attempts to formulate relevant guidelines and standards, yet a universal solution has not been found.

Among the critical ongoing challenges are the ability of autonomous systems to adequately respond to unpredictable events and rare scenarios ("edge cases"), especially in chaotic urban environments; achieving high levels of public trust and technology acceptance; ensuring interoperability of systems from different manufacturers; and addressing potential socioeconomic issues related to labor market transformations in the transport sector. The cost of comprehensive autonomous driving systems, while decreasing, remains high, limiting their widespread adoption in affordable market segments.

Finally, analyzing **the prospects for further implementation**, it is evident that the 2020–2025 period has laid the foundation for more active integration of unmanned technologies in the near future. Progress in technology, the gradual formation of a legislative framework, and accumulated testing experience pave the way for expanding application areas. The most realistic prospects for the coming years include the deployment of autonomous systems in controlled environments: shuttles in airports, university campuses, and large industrial zones; robotic last-mile delivery services; and highly automated freight transport on highway routes.

The emergence of commercial robotaxi services in select cities indicates the technology's gradual approach to consumers, though full autonomy (Level 5 per SAE classification), enabling vehicles to operate anywhere and in any conditions without human intervention, remains a more distant prospect. Further diversification of applications is expected in agriculture, construction, and municipal services. The success of further implementation will depend on the synergy of efforts among developers, legislators, infrastructure operators, and society as a whole, aimed at resolving remaining technological, legal, and social issues.

The subsequent sections of this article will provide a detailed examination of each of these aspects, offering an in-depth analysis of technological innovations, regulatory changes, key challenges, and substantiated forecasts for the future of unmanned transport based on data and trends observed in 2020–2025.

In this study, the methods of analytical review, comparative analysis, and systematization of literary and regulatory sources were applied.

Keywords: unmanned vehicles, autonomous driving, artificial intelligence, sensor systems, LIDAR, radars, GPS, legal regulation, ethical dilemmas, road safety, technical challenges, unmanned trucks, infrastructure for autonomous vehicles, Tesla, Waymo, Google, Kodiak Robotics, Nuro.

Артюх Олександр Миколайович кандидат технічних наук, доцент кафедри «Автомобілі, теплові двигуни та гібридні енергетичні установки» НУ «Запорізька політехніка», м. Запоріжжя, тел.: +38(061) 764–26–47, https://orcid.org/0000–0002–5043–7038

Рубан Дмитро Петрович доктор технічних наук, професор, кафедри автомобілів та тракторів Львівського національного університету природокористування, м. Дубляни, http://orcid.org/0000-0002-0671-3226

Тарасенко Олександр Віталійович старший викладач кафедри «Транспортні технології» НУ «Запорізька політехніка», м. Запоріжжя, тел.: +38(061) 7698-560, https://orcid.org/0000-0001-7882-5481

Петрюк Юрій Іванович аспірант «Автомобілі, теплові двигуни та гібридні енергетичні установки» НУ «Запорізька політехніка», м. Запоріжжя, тел.: +38 (099) 707-97-06, https://orcid.org/0009-0003-4543-1744

Рубан Ганна Яківна викладач, Черкаський державний бізнес-коледж, м. Черкаси, тел.: +38(050) 732–20–88, https://orcid.org/0000-0002-8702-8430

БЕЗПІЛОТНИЙ ТРАНСПОРТ. СУЧАСНІ ТЕХНОЛОГІЇ, ВИКЛИКИ ТА ПЕРСПЕКТИВИ

Анотація. Стаття пропонує поглиблений огляд сучасного етапу розвитку безпілотного транспорту, синтезуючи інформацію про технологічні інновації, законодавчі ініціативи, подолані та актуальні виклики, а також прогнозуючи майбутні напрямки його еволюції в контексті глобальних тенденцій та попередніх досліджень. Щоб досягти поставленої мети, дослідження зосереджується на аналізі ключових змін, що відбулися саме в період 2020–2025 років, відповідаючи на фундаментальні питання щодо прогресу та перешкод на шляху до автономної мобільності.

Розглядаючи перше ключове питання – **про нові технології, що з’явилися або зазнали суттєвого розвитку за останні роки**, – слід відзначити значний прогрес у вдосконаленні сенсорних систем та алгоритмів обробки даних. У період 2020-2025 років спостерігалося не лише покращення характеристик існуючих сенсорів, таких як LiDAR (Light Detection and Ranging), радарів та камер (зокрема, підвищення роздільної здатності, дальності дії та стійкості до перешкод), але й активне зниження їхньої вартості, що наблизило технологію до масового ринку.

Важливим трендом стало вдосконалення технологій *сенсорного злиття (sensor fusion)* тобто об'єднання інформації сенсорів, які дозволяють інтегрувати дані з різних типів датчиків для створення більш повної, точної та надійної картини навколишнього середовища. Паралельно відбувався стрибок у розвитку алгоритмів штучного інтелекту, особливо глибокого навчання (deep learning), що дозволило суттєво підвищити якість розпізнавання об'єктів (пішоходів, транспортних засобів, дорожніх знаків), прогнозування їхньої поведінки та прийняття рішень в складних дорожніх ситуаціях.

Розвиток комунікаційних технологій V2X (Vehicle-to-Everything) також набрав обертів, відкриваючи можливості для взаємодії автомобілів між собою та з інфраструктурою, що є критично важливим для підвищення безпеки та ефективності руху, особливо в умовах щільного трафіку. Крім того, значну роль відіграли вдосконалення високоточних карт (HD-карт) та розвиток потужних обчислювальних платформ, здатних обробляти величезні масиви даних в режимі реального часу, а також широке використання симуляційних середовищ для віртуального тестування та валідації алгоритмів керування.

Друге, не менш важливе питання, стосується **динаміки змін у законодавчій базі**. Період 2020–2025 років став переломним у сенсі переходу від переважно експериментального регулювання до формування більш системних підходів. Багато країн світу, включаючи держави ЄС, США, Китай та Японію, активно розробляли та впроваджували нові закони та нормативи, що стосуються тестування безпілотних автомобілів на дорогах загального користування, їх сертифікації та вимог до безпеки.

Знаковими стали перші спроби врегулювати питання комерційної експлуатації, зокрема, для сервісів роботаксі та автономних вантажних перевезень у певних географічних зонах або на визначених маршрутах. На міжнародному рівні активізувалася робота в рамках Економічної комісії ООН для Європи (UNECE) щодо гармонізації технічних регламентів, зокрема, стосовно систем утримання смуги руху (ALKS) та інших функцій автомати-зованого водіння.

Проте, незважаючи на значний прогрес, законодавча база все ще залишається фрагментованою, а питання юридичної відповідальності у разі ДТП за участю високоавтоматизованих транспортних засобів, стандарти кібербезпеки та захисту даних, а також нормативне закріплення етичних принципів роботи ШІ потребують подальшого ретельного опрацювання та узгодження на національному та міжнародному рівнях.

Третє дослідницьке питання фокусується на **викликах, які вдалося подолати, та тих, що залишаються актуальними**. За останні п'ять років розробники досягли помітного прогресу в підвищенні надійності систем сприйняття в складних умовах, хоча забезпечення бездоганної роботи в екстремальних погодних умовах (сильний дощ, снігопад, туман) або при поганому освітленні все ще є серйозним технологічним бар'єром.

Значну увагу було приділено питанням кібербезпеки, розробці протоколів захисту від зламів та несанкціонованого доступу, хоча ця загроза залишається постійною і вимагає невпинної уваги. Публічний дискурс щодо етичних аспектів, зокрема програмування поведінки автомобіля в неминучих аварійних ситуаціях, активізувався, що спонукало до перших спроб формування відповідних рекомендацій та стандартів, однак універсального рішення досі не знайдено.

Серед викликів, що залишаються критичними, – здатність автономних систем адекватно реагувати на непередбачувані події та рідкісні сценарії («edge cases»), особливо в хаотичному міському середовищі; досягнення високого рівня суспільної довіри та прийняття технології; забезпечення інтероперабельності систем різних виробників; а також вирішення потенційних соціально-економічних проблем, пов'язаних із трансформацією ринку праці в транспортній галузі. Вартість комплексних систем автономного водіння, хоч і знижується, все ще залишається високою, що обмежує їх масове впровадження в доступних сегментах ринку.

Нарешті, аналізуючи **перспективи подальшого впровадження**, стає очевидним, що період 2020-2025 років заклав фундамент для більш активної інтеграції безпілотних технологій у найближчому майбутньому. Прогрес у технологіях, поступове формування законодавчої бази та накопичений досвід тестування відкривають шлях до розширення сфер застосування. Найбільш реалістичними на найближчі роки виглядають перспективи впровадження автономних систем у контрольованих середовищах: шатли в аеропортах, університетських кампусах, великих промислових зонах; роботизовані служби доставки «останньої милі»; а також високоавтоматизовані вантажні перевезення на магістральних маршрутах.

Поява комерційних сервісів роботаксі в окремих містах свідчить про поступове наближення технології до споживача, хоча повна автономність (Рівень 5 за класифікацією SAE), що дозволяє транспортному засобу пересуватися будь-де і за будь-яких умов без втручання людини, все ще розглядається як більш віддалена перспектива. Очікується подальша диверсифікація застосувань у сільському господарстві, будівництві та комунальному господарстві. Успішність подальшого впровадження залежатиме від синергії зусиль розробників, законодавців, інфраструктурних операторів та суспільства в цілому, спрямованих на вирішення залишкових технологічних, правових та соціальних питань.

Подальші розділи цієї статті детально розглянуть кожен із зазначених аспектів, надаючи поглиблений аналіз технологічних інновацій, регуляторних змін, ключових викликів та обґрунтовані прогнози щодо майбутнього безпілотного транспорту на основі даних та тенденцій, що спостерігалися у 2020–2025 роках.

У даному дослідженні застосовано метод аналітичного огляду, порівняльного аналізу та систематизації літературних і нормативних джерел.

Ключові слова: безпілотні автомобілі, автономне водіння, штучний інтелект, сенсорні системи, LIDAR, радари, GPS, правове регулювання, етичні дилеми, безпека дорожнього руху, технічні виклики, безпілотні вантажівки, інфраструктура для безпілотників, Tesla, Waymo, Google, Kodiak Robotics, Nuro.

Problem Statement. The modern world stands on the threshold of a transportation revolution, driven by the rapid development and integration of autonomous vehicle technologies. Unmanned transport is no longer merely a futuristic concept but is becoming a tangible factor poised to fundamentally transform the paradigms of mobility, logistics, urban planning, and social interaction.

The significance of this transformation cannot be overstated: the potential to enhance road safety by minimizing human error, optimize traffic flows and reduce congestion, increase the efficiency of freight transport, and improve transport accessibility for people with disabilities and the elderly represents only a fraction of the anticipated benefits fueling intensive research and development in this field worldwide. Global challenges such as urbanization, the need to reduce greenhouse gas emissions, and the pursuit of sustainable solutions for transportation systems further underscore the relevance and urgency of implementing autonomous technologies.

This article aims to provide a comprehensive analysis of key achievements, challenges, and trends in the field of unmanned transport from 2020 to 2025. This time period was chosen deliberately, as it marks significant progress from experimental developments to the initial stages of commercial implementation and large-scale testing in real-world conditions.

This study is a logical continuation of the previous article, “Evolution of Self-Driving Cars: From Experiments to Everyday Use” [1], which focused on the historical evolution of autonomous driving technologies and examined the fundamental stages of concept development and foundational systems. While the previous study laid the groundwork for understanding the origins and gradual development of unmanned systems, this work concentrates on the dynamics of recent years, analyzing how the transition from theoretical advancements and laboratory testing to practical application and integration into existing transportation infrastructure has unfolded.

The relevance of the chosen topic stems not only from technological progress but also from its close connection to global contemporary trends. The digitalization of the economy, advancements in artificial intelligence, the Internet of Things (IoT), 5G networks, and improvements in sensor technologies have created a favorable foundation for accelerating the development of autonomous systems.

At the same time, the growing focus on sustainable mobility and the concept of “smart cities” positions unmanned transport as a key component of future infrastructure capable of addressing the complex challenges of modern megacities. Thus, analyzing the current state of this field is crucial not only from an engineering and technical perspective but also in the context of socioeconomic and environmental transformations.

This study employs the methods of analytical review, comparative analysis, and systematization of literary and regulatory sources.

Analysis of Recent Research and Publications. In analyzing the development of unmanned vehicles and their impact on transportation systems, it is essential to consider the literature [1–35], which covers mechatronics, artificial intelligence, sensor systems, legal issues, and the prospects for autonomous transport development. The literature review indicates that autonomous transport is a complex research field integrating technical, legal, and ethical aspects. These issues are explored in greater detail in the article "Evolution of Self-Driving Cars: From Experiments to Everyday Use" [1], which analyzes the stages of autonomous vehicle development, modern technologies, challenges, and prospects for their integration into everyday life.

1. Within the scope of this study, key questions are posed, the answers to which will provide a comprehensive understanding of the current state and future prospects of unmanned transport development. First, **what new technologies and innovative solutions have emerged or gained significant traction between 2020 and 2025?** This pertains to both advancements in hardware (LiDAR, radars, cameras, and computing platforms) and breakthroughs in software, particularly in algorithms for environmental perception, route planning, decision-making, and vehicle-to-everything (V2X) communications. Special attention is given to the development of artificial intelligence (AI) and machine learning systems, which form the core of autonomy.

Second, an equally critical aspect is the analysis of **how the legislative and regulatory framework governing the development**, testing, and operation of unmanned vehicles has evolved. The period from 2020 to 2025 is characterized by active efforts from numerous countries and international organizations to establish relevant standards, certification protocols, and frameworks for determining legal liability in incidents involving autonomous systems. Without an adequate legal framework, widespread adoption of this technology remains unfeasible, making the dynamics of change in this area critically important.

Third, it is necessary to investigate **which technological, ethical, and social challenges have been partially or fully addressed over the past five years, and which issues remain the most pressing**. These challenges include ensuring the reliability and safety of systems in extreme weather conditions or complex traffic scenarios, guaranteeing cybersecurity and protection against malicious attacks, addressing ethical dilemmas related to programming vehicle behavior in emergency situations (the "trolley problem"), and tackling issues of public perception and trust in new technologies. Analyzing progress in resolving these challenges will help assess the feasibility of forecasts regarding the timeline for mass adoption.

Finally, the fourth key question concerns **the prospects for further implementation of autonomous transport.** Based on the analysis of achievements, regulatory changes, and existing challenges, this study aims to outline the most likely scenarios for the industry's development in the coming years, identify potential areas of application (ranging from individual passenger vehicles to public transport, freight logistics, and specialized equipment), and evaluate the potential socioeconomic impact of integrating these technologies into everyday life.

2. Technical Progress in the Field of Autonomous Transport (2020–2025).

The period from 2020 to 2025 has been pivotal for the technological landscape of autonomous transport. These years marked a qualitative leap in the development of key components underpinning automated driving systems. Significant investments in research and development, intensified competition among technology giants and automotive manufacturers, and accumulated experience from real-world testing have driven substantial progress in both hardware and software solutions. Central to this progress is the enhancement of environmental perception systems, as their accuracy, reliability, and responsiveness are critical to the safety and efficiency of unmanned driving.

2.1. Development of Sensor Systems.

Sensor systems serve as the "sensory organs" of autonomous vehicles, enabling them to "see" and "sense" their surroundings. Between 2020 and 2025, developers focused their efforts on improving three primary types of sensors—LiDAR, radar, and cameras—while also advancing their effective integration into unified multi-sensor platforms.

LiDAR (Light Detection and Ranging) systems have seen some of the most notable advancements. Previously, these devices were bulky, expensive, and mechanically complex (often relying on rotating components). However, during the analyzed period, significant progress was made in the development and commercialization of solid-state LiDARs. These devices, which lack moving parts, are more compact, reliable, and potentially far more cost-effective for mass production.

Parallel improvements in key characteristics included extended detection ranges (often exceeding 200–300 meters for low-reflectivity objects), enhanced resolution (enabling finer detail recognition and more precise object shape identification), wider fields of view, and increased resilience to interference from other LiDAR systems. These advancements have enabled the generation of significantly more detailed and accurate 3D point clouds, which form the basis for constructing environmental maps and detecting obstacles. Although cost reductions have been gradual, they have begun to make LiDAR more accessible for integration not only in premium models but also in mid-range vehicles designed for higher levels of automation (Level 3 and above).

Radar systems have also undergone substantial evolution. Traditional radars, widely used in adaptive cruise control and emergency braking systems due to their ability to operate in all weather conditions (rain, snow, fog) and measure object velocity via the Doppler effect, gained new capabilities. A key development was the emergence of high-resolution radars, also known as imaging radars or 4D radars.

Unlike previous generations, these systems can not only detect objects and measure their distance and speed but also determine their angular position (azimuth and elevation) with significantly greater accuracy. This enables the creation of a "radar image" of the environment, distinguishing closely spaced objects (e.g., a car and a motorcyclist nearby), improving object classification (pedestrian, car, truck), and more accurately detecting static obstacles—a weakness of older radars. Their ability to "see" through obstructions (e.g., a vehicle ahead of the vehicle in front) and reliability in adverse weather make modern radars an indispensable component of multi-sensor systems.

Cameras, as the most widespread and information-rich sensors, have also seen significant advancements. Progress has been made in both hardware and image-processing algorithms. Between 2020 and 2025, cameras with higher resolutions (up to 8 megapixels and beyond) became widespread, featuring improved high dynamic range (HDR) capabilities, which allow simultaneous visibility of details in both very bright and very dark areas of a scene (e.g., when exiting a tunnel), and enhanced sensitivity in low-light conditions.

In addition to standard visible-spectrum cameras, infrared (thermal) cameras have been increasingly adopted, effectively detecting pedestrians and animals at night or in poor visibility conditions, regardless of lighting. However, the most significant changes occurred in software: advancements in neural networks and deep learning have enabled computer vision systems to extract highly detailed semantic information from video streams, including recognizing and classifying various objects, identifying drivable space, reading road signs and traffic signals, analyzing road markings, and understanding complex traffic scenarios.

A key achievement of the 2020–2025 period was **the integration of multi-sensor platforms** and the refinement of **sensor fusion** technologies. The recognition that no single sensor type is ideal in all conditions—cameras are sensitive to lighting and weather, LiDAR to fog and heavy precipitation, and radar has lower resolution—necessitated the combination of their data.

Modern autonomous driving systems employ sophisticated algorithms, ranging from classical Kalman filters to advanced AI-based methods, to integrate information from multiple sources, compensating for the limitations of one sensor with the strengths of others. This enables the creation of a unified, coherent, redundant, and significantly more reliable model of the environment, which is critical for safe decision-making by the control system.

Prominent **examples** of comprehensive solutions reflecting these trends include developments by leading industry players.

- **Tesla Hardware 4.0 (HW4)**, introduced around 2023, represents an evolution of the company's approach, which historically relied heavily on cameras. HW4 incorporates significantly higher-resolution cameras (approximately 5 MP compared to 1.2 MP in HW3) with improved characteristics and, according to available data, integrates a new, more advanced radar (possibly a high-resolution "Phoenix" radar). This indicates a partial shift away from the previous "vision-only" strategy toward a multi-sensor approach. All of this is supported by an updated, more powerful computing platform.

- **Mobileye SuperVision™** is a system that also heavily relies on cameras (typically 11 cameras for 360-degree coverage) but integrates them with radar and, optionally, LiDAR data. Positioned as a solution for advanced driver-assistance systems (ADAS) evolving toward Level 2+ or Level 3 ("hands-off") autonomous driving functions, the system leverages powerful Mobileye EyeQ® processors to process data and enable features like navigation on autopilot. It has been adopted by several manufacturers, including Geely, Zeekr, and Porsche.
- **NVIDIA Drive Orin™** is an example of a high-performance computing platform (System-on-a-Chip, SoC) specifically designed to meet the demands of autonomous driving. While not a sensor itself, it serves as the "brain," capable of processing vast streams of data from various sensors (dozens of cameras, LiDARs, and radars) in real time. Drive Orin™ provides the computational power needed to execute complex artificial intelligence algorithms, sensor fusion, and route planning, which are essential for achieving autonomy at Levels 3, 4, and beyond. The platform has been adopted by numerous automakers (Mercedes-Benz, Volvo, Jaguar Land Rover) and autonomous driving technology developers as the foundation for their systems.

Thus, the period from 2020 to 2025 demonstrated significant advancements in the "senses" of autonomous vehicles, driven by progress in individual sensor technologies and, more importantly, their deep integration and synergy within multi-sensor platforms, supported by robust computational capabilities. This established the technological foundation for transitioning to more sophisticated and reliable autonomous driving functions.

2.2. Development of Artificial Intelligence Algorithms

If sensor systems are the "eyes and ears" of an autonomous vehicle, artificial intelligence (AI) algorithms serve as its "brain," responsible for interpreting sensor data, understanding complex traffic situations, predicting events, and making safe and efficient driving decisions. The period from 2020 to 2025 was marked by revolutionary achievements in AI, particularly due to the rapid advancement of deep learning methods and their application to specific autonomous driving tasks.

Deep learning for image processing and pattern recognition became a true catalyst for progress in perception systems. Convolutional Neural Networks (CNNs) demonstrated unprecedented effectiveness in tasks related to visual data analysis. During this period, not only was there an improvement in the accuracy and reliability of object recognition (vehicles, pedestrians, cyclists, road signs, lane markings) using cameras, but significant advancements were also made in more complex tasks.

In particular, methods for **semantic segmentation**, which classify each pixel in an image (e.g., road, sidewalk, building, sky), and **instance segmentation**, which not only classifies but also distinguishes individual objects within a class, gained substantial development. These technologies provide a much deeper understanding of a scene compared to simple object detection using bounding boxes. Additionally, approaches to **3D object recognition** directly from camera data or through the fusion of camera and LiDAR/radar data were actively developed, enabling more precise determination of an object's position, size, and orientation in three-dimensional space.

Another critical area of advancement was the application of AI to develop **predictive behavioral models**. For safe navigation, an autonomous vehicle must not only identify other road users but also anticipate their actions over the next few seconds. In this context, **Recurrent Neural Networks (RNNs)**, particularly those with Long Short-Term Memory (LSTM) architectures, and Transformer-based architectures, which analyze temporal sequences of data (e.g., object movement trajectories), gained widespread use for predicting future developments.

Developers created increasingly sophisticated models that account not only for an object's movement history but also the situational context: the presence of intersections, traffic signals, pedestrian crosswalks, and interactions among different road users. Accurate prediction of the intentions of other drivers and pedestrians is a key element in achieving smooth, "human-like," and safe driving behavior for autonomous vehicles, allowing them to proactively adjust their speed and trajectory. These predictive capabilities directly impact the quality of motion planning algorithms, which also saw improvements, particularly through the application of **Reinforcement Learning** and **Imitation Learning** methods.

One of the most critical factors enabling such rapid progress in the development of AI algorithms for autonomous driving has been the widespread adoption of training and testing in virtual environments (simulators). Modern deep learning models require vast amounts of diverse data for effective training. Collecting such data in the real world is extremely costly, time-consuming, and not always safe. It is particularly challenging to gather sufficient examples of rare but critically important traffic situations, known as "edge cases" or "corner cases."

This is where simulation proves invaluable. Highly accurate virtual worlds allow developers to generate virtually unlimited amounts of synthetic data, replicating any weather conditions, time of day, road types, and traffic scenarios. Simulators enable safe modeling of dangerous situations—such as a pedestrian suddenly stepping onto the road, unexpected maneuvers by other vehicles, or equipment failures—and train AI to respond appropriately.

This approach not only accelerates the training process but also significantly enhances the validation and verification of models before real-world testing. Modern simulators have achieved a high level of realism, replicating not only the visual environment but also the physics of vehicle motion and sensor functionality (generating synthetic data for LiDAR, radar, and cameras while accounting for their characteristics and potential noise).

Leading companies in the autonomous driving industry actively use simulation as an integral part of their development process. For example, **Waymo**, a pioneer in the field, operates its robust simulation platform (known as Carcraft/Simulation City), where its "Waymo Driver" system "drives" millions of virtual miles daily. This enables testing of new software versions, recreating complex real-world scenarios, and training AI on data that would be impossible or unsafe to obtain otherwise. Similarly, **Aurora Innovation**, which develops technologies for both passenger vehicles and trucks, relies on its comprehensive virtual testing toolkit (Aurora Virtual Testing Suite). They use simulation to evaluate billions of potential scenarios, verify system safety in edge cases, and accelerate the development of their universal "Aurora Driver" software stack.

Thus, advancements in artificial intelligence algorithms, supported by powerful deep learning capabilities and strategic use of virtual environments for training and testing, have been a key factor in enhancing the "intelligence," adaptability, and reliability of autonomous driving systems during the 2020–2025 period. This has facilitated a transition from demonstrating basic capabilities to deploying more complex functions in real-world operational conditions.

2.3. Resilience in Challenging Conditions

Despite impressive progress in sensor technologies and artificial intelligence algorithms, ensuring stable and safe operation of autonomous vehicles in challenging external conditions remained one of the most significant hurdles for developers during the 2020–2025 period and continues to be relevant. The ability of a system to function reliably not only in ideal conditions but also during **fog, rain, snow, or on roads with poor surface conditions or faded markings** is critical for widespread adoption and gaining public trust.

Adverse weather conditions pose a significant challenge for most sensor systems. **Fog, heavy rain, and snowfall** can severely impair visibility for cameras, scatter or weaken LiDAR signals, and complicate accurate object detection and distance measurement. While radars are more resilient to such conditions, their resolution may be insufficient for recognizing fine details or accurately classifying objects in dense precipitation. Additionally, precipitation can obscure road markings and signs, which are crucial reference points for navigation and positioning systems. Snow and ice on road surfaces not only alter the visual appearance of the environment, potentially misleading perception systems, but also drastically affect vehicle dynamics—traction, braking distance, and handling.

Poor road surface conditions also present significant obstacles. Potholes, cracks, and uneven surfaces can cause discomfort or damage to the vehicle and require the control system to promptly detect and safely navigate around them or adjust speed accordingly. **Faded, unclear, or absent road markings** deprive the system of critical visual cues, complicating lane-keeping, especially on curves or multi-lane roads. Operating on **unstructured roads (e.g., dirt roads)** or in areas with active road construction demands an even higher level of adaptability and the ability to navigate using less obvious indicators.

To address these challenges during the 2020–2025 period, developers adopted a comprehensive approach combining hardware and software solutions. First, this involved further advancements in sensor technologies: the use of higher-resolution radars that better "see" through precipitation; the adoption of cameras with expanded dynamic range and thermal imaging cameras effective in low-visibility conditions; and the development of LiDAR systems operating at wavelengths less susceptible to scattering in fog or rain.

Second, improvements in sensor **fusion algorithms** played a crucial role, enabling intelligent combination of data from multiple sources and prioritizing the most reliable information under specific conditions. Third, **AI models** were developed and trained on large datasets incorporating recordings from diverse challenging weather and road conditions (both real and simulator-generated). These models became more resilient to "noisy" data and learned to rely on alternative cues for localization and navigation, such as high-definition (HD) maps, GPS/IMU data, or recognition of road edges and other stable landmarks. Additionally, physical solutions were implemented, such as **sensor cleaning systems** (washers, brushes, air blowers) to maintain functionality in conditions involving dirt or precipitation, and **adaptive control algorithms** that automatically reduce speed and increase following distance in adverse conditions.

Different companies adopted varied strategies for operating in challenging conditions, often defining a specific **Operational Design Domain (ODD)**—a set of conditions under which their system can operate safely with guaranteed performance.

- **Nuro**, a company developing small unmanned vehicles for local goods delivery, exemplifies reliance on a constrained ODD. Their robotic couriers, R2 and R3, operate at low speeds (typically up to 45 mph or ~72 km/h) primarily in residential areas and urban streets with good road surfaces. While their systems must handle rain or minor road imperfections, the company can limit or suspend operations during extreme weather conditions (heavy rain, snowfall, or icy roads) that fall outside the defined ODD. Their design also incorporates integrated sensors and cleaning systems optimized for their specific tasks and operating conditions.
- **Kodiak Robotics**, specializing in autonomous driving technologies for long-haul trucking, faces different challenges related to high speeds and long distances. Their approach emphasizes a high degree of sensor redundancy, integrated into modular "SensorPods" mounted on the sides of the truck cab. These pods contain cameras, LiDAR, and radars, designed for reliability, vibration resistance, and ease of maintenance. Kodiak actively develops software to enable the "Kodiak Driver" system to better interpret data in rain or fog, common on highways, and adapt its driving style. They also leverage detailed HD maps and robust positioning systems. However, like most developers, Kodiak acknowledges

the current limitations of the technology and may restrict autonomous operation in extremely challenging weather conditions, transferring control to a safety driver or halting movement.

Despite significant progress achieved during the 2020–2025 period through advancements in hardware, software algorithms, and strategic ODD definitions, achieving full all-weather and all-road autonomy (particularly for Levels 4 and 5) remains a key unresolved challenge. Further innovations in sensors, AI algorithms, and testing methodologies are essential to enable unmanned vehicles to operate safely and reliably in any conditions faced by human drivers.

3. Legislative and Regulatory Framework

Parallel to the intensive technological advancements described in the previous section, the period from 2020 to 2025 was marked by active development of the legislative and regulatory framework necessary for the implementation of autonomous transport. The successful and safe integration of unmanned technologies into transportation systems is impossible without clear rules, standards, and legal frameworks governing their development, testing, certification, and operation. The absence of such frameworks creates uncertainty for manufacturers, hinders investment, and undermines public trust. Consequently, the efforts of legislators and regulatory bodies at national and international levels gained particular significance during this period, marking a transition from a predominantly experimental phase to the establishment of conditions for the real-world deployment of automated driving systems.

3.1. International Initiatives and Standards

Given the globalization of the automotive industry and the cross-border nature of transport flows, international cooperation and harmonization of standards are critical for effective regulation of autonomous transport. This approach helps avoid market fragmentation, simplifies certification procedures for manufacturers operating in multiple countries, and ensures a consistently high level of safety. Two key trends became particularly prominent in 2020–2025: progress in developing specific technical regulations under the auspices of the United Nations and the integration of autonomous transport issues into broader strategic initiatives, such as the European Green Deal.

A significant milestone was the advancement of work within the **World Forum for Harmonization of Vehicle Regulations (WP.29)** of the United Nations Economic Commission for Europe (UNECE). This forum serves as a key international platform for developing unified technical regulations and safety standards for vehicles. A major achievement was the adoption in June 2020 and entry into force in January 2021 of **UN Regulation No. 157**, the first legally binding international regulation establishing requirements for **Automated Lane Keeping Systems (ALKS)** for passenger vehicles. ALKS are Level 3 automation systems, as classified by SAE, capable of fully controlling longitudinal and lateral vehicle movement on highways under specific conditions, allowing the driver to temporarily disengage from driving tasks.

UN Regulation No. 157 specifies the operational conditions for such systems: they are designed for use exclusively on roads where pedestrians and cyclists are prohibited and which have a physical separation of oncoming traffic lanes (i.e., highways). Initially, the maximum operational speed for ALKS was limited to 60 km/h, making them primarily suitable for dense traffic or congestion scenarios.

However, recognizing the rapid pace of technological development, UNECE actively worked to expand the regulation's scope. By early 2025, amendments had been adopted to increase the maximum operational speed of ALKS to 130 km/h and include capabilities for automated lane changes, significantly enhancing the functionality of Level 3 systems. The regulation also imposes stringent requirements, including: a **Driver Availability Recognition System** to ensure the driver can quickly resume control; a clear **Human-Machine Interface (HMI)** to inform the driver of the system's status; a **Data Storage System for Automated Driving (DSSAD)**, or "black box," to record system parameters and driver actions; and overall system safety and fault tolerance.

The adoption and ongoing development of UN Regulation No. 157 established a unified basis for the certification (type approval) of vehicles with ALKS functions in countries party to the 1958 Agreement (including EU countries, the United Kingdom, Japan, South Korea, Australia, and others), marking a critical step toward the legalization and proliferation of Level 3 technologies. Work within UNECE continues to expand regulations to cover additional automated functions, other vehicle types (including trucks and buses), and more complex operating conditions (e.g., urban environments).

Another important context for the development of autonomous transport regulation, particularly in Europe, was the **European Green Deal**, an ambitious European Union strategy launched in late 2019 to achieve climate neutrality by 2050. The transport sector, which accounts for a significant share of greenhouse gas emissions, is a key focus of transformation under this strategy. Autonomous transport is viewed as a technology with the potential to contribute to the Green Deal's objectives.

It is anticipated that automation, particularly when combined with electrification and connectivity (**Connected Mobility**), can lead to: improved energy efficiency through optimized driving styles (smooth acceleration and braking); the ability to form truck convoys (**platooning**) to reduce aerodynamic drag; reduced congestion through better coordination of traffic flows; enhanced logistics and transport efficiency; and the promotion of multimodal transport by using autonomous shuttles for "first/last mile" connectivity to public transport hubs.

The EU's strategies for **Cooperative, Connected, and Automated Mobility (CCAM)** and related research and innovation programs (e.g., under Horizon

Europe) actively support the development and pilot implementation of such solutions, often emphasizing the synergy between automation, decarbonization, and transport digitalization. At the same time, potential risks are acknowledged, such as the possible increase in total mileage due to the enhanced convenience of individual transport, necessitating balanced policies to maximize the positive environmental impact of autonomous technologies.

Thus, international efforts during the 2020–2025 period were directed at both establishing specific technical standards to enable the safe deployment of early high-level automation systems and integrating autonomous transport into long-term strategic frameworks related to sustainable development and climate protection goals. These initiatives form a critical foundation for the further evolution of the regulatory landscape in this dynamic field.

3.2. Changes in Legislation in Leading Countries

While international agreements, such as UN Regulation No. 157, provide an important foundation for harmonization, the actual implementation and regulation of autonomous transport largely depend on national legislation. During the 2020–2025 period, leading countries worldwide actively adapted their legal systems to create conditions for testing and the gradual deployment of unmanned technologies, although the approaches and pace of these changes varied significantly.

In the **United States**, regulation is characterized by a two-tier system: federal and state-level. At the federal level, the **National Highway Traffic Safety Administration (NHTSA)** plays a key role. Between 2020 and 2025, NHTSA issued updated guidelines and policy statements, such as "Automated Driving Systems: A Vision for Safety," aimed at fostering innovation while ensuring safety. A significant focus was placed on updating the **Federal Motor Vehicle Safety Standards (FMVSS)** to accommodate vehicles without traditional controls (e.g., steering wheels or pedals), though this process has been gradual. NHTSA also introduced requirements for manufacturers to report crashes involving vehicles equipped with Advanced Driver Assistance Systems (ADAS, Level 2) and Automated Driving Systems (ADS, Level 3+), enabling data collection to better understand the real-world safety of these technologies.

At the same time, the primary regulation of testing and deployment of autonomous vehicles occurs at the state level. States such as California, Arizona, Nevada, Florida, and Michigan have emerged as leaders in establishing specific regulations and "autonomous zones" for testing, issuing permits to companies for trials and, in some cases, commercial operations (e.g., robotaxi services). This approach has resulted in a somewhat fragmented ("patchwork") regulatory landscape in the U.S., with requirements varying significantly from state to state, posing challenges for companies aiming to operate nationwide.

The **European Union** has pursued a more harmonized approach. As noted, UN Regulation No. 157 on ALKS was incorporated into the EU's legal framework, becoming mandatory for new vehicle types. Additionally, the EU updated its general vehicle safety legislation, such as the **General Safety Regulation (GSR)**, to include requirements for mandatory equipping of vehicles with Advanced Driver Assistance Systems (ADAS), which also supports the transition to higher levels of automation.

During the 2020–2025 period, the European Commission launched several initiatives and legislative proposals aimed at creating a favorable ecosystem for **Cooperative, Connected, and Automated Mobility (CCAM)**. These efforts include regulating access to vehicle data (crucial for developing and operating data-driven services), ensuring cybersecurity for connected vehicles, and applying the forthcoming **AI Act** to autonomous driving systems. Overall, EU policy is geared toward establishing a single market for autonomous technologies with high standards for safety, transparency, and consumer protection, while leveraging these technologies to achieve sustainable development goals outlined in the European Green Deal.

China demonstrated an exceptionally dynamic and state-driven approach to autonomous transport development, viewing it as a strategically important sector. The Chinese government actively supports innovation through national strategies for AI and intelligent transport systems, substantial public investments, and the creation of large-scale pilot zones for **Intelligent Connected Vehicles (ICVs)** in numerous cities. Between 2020 and 2025, China adopted increasingly specific national and local regulations governing public road testing and the initial stages of commercial operations for robotaxis and autonomous trucks in designated zones (sometimes without a safety driver onboard). The **Ministry of Industry and Information Technology (MIIT)** and the **Ministry of Transport** play pivotal roles in shaping standards and regulations. Thanks to this support and a vast domestic market, China has become one of the global leaders in the pace of testing and deployment of autonomous technologies, particularly in urban environments and logistics.

Japan is also among the leading countries in regulating autonomous driving. As early as 2019–2020, Japan amended its **Road Traffic Act** and **Road Transport Vehicle Act**, legalizing the use of Level 3 systems on public roads under specific conditions. This enabled Honda to launch the Legend model with the “Traffic Jam Pilot” system in 2021, the world’s first certified Level 3 vehicle. Japan places significant emphasis on developing robust procedures for evaluating and verifying the safety of automated systems. The government actively supports research and development, viewing autonomous transport as a vital tool for addressing social challenges, such as an aging population and ensuring mobility in rural areas. The country continues to work on establishing a regulatory framework for higher levels of automation and a broader range of applications.

In summary, during the 2020–2025 period, leading countries worldwide adopted diverse but equally proactive approaches to shaping the legislative landscape for autonomous transport. From the flexible yet fragmented system in the

U.S. to the harmonized approach of the EU and the strong state-driven support in China and Japan, these efforts were aimed at enabling safe testing and the gradual implementation of technologies that are transforming the future of mobility.

3.3. Issues of Legal Liability

One of the most complex and contentious issues accompanying the development of autonomous transport is the question of legal liability in the event of road traffic accidents (RTAs) involving such vehicles. The traditional liability system, which primarily hinges on the fault of the human driver, becomes inadequate or requires significant modification when control of the vehicle is fully or partially delegated to an automated system. This issue became the subject of intense discussions among lawyers, insurers, manufacturers, and policymakers during the 2020–2025 period. While definitive solutions have yet to be established, new approaches began to take shape.

The core challenge lies in determining fault in an RTA when an automated driving system (particularly Level 3 or higher) was in control. If the system was operating the vehicle at the time of the accident, who bears responsibility: the "driver," who may have been legally relieved of the obligation to constantly monitor the system; the vehicle manufacturer; the software developer (AI); or the supplier of individual components (e.g., sensors)? In response to these questions, new approaches to defining liability have been debated. There is a growing trend toward holding the manufacturer or system developer accountable in cases where an RTA results from a malfunction or error in the automated system, based on the principle of **product liability**.

This, in turn, underscores the critical importance of the availability and analysis of data from onboard recorders (**Data Storage System for Automated Driving, DSSAD**, or **Event Data Recorders, EDR**), which must document who or what was controlling the vehicle at the time of the incident, the commands issued by the system, and whether it was functioning within its designated parameters and **Operational Design Domain (ODD)**. Requirements for such "black boxes" have already been incorporated into international standards, such as UN Regulation No. 157.

There has also been active discussion about the need to reform insurance systems. The future may lie in models where insurance covers not so much the driver's liability but the vehicle and its automated system itself. Some jurisdictions have begun exploring options for introducing **no-fault compensation schemes** for certain types of RTAs involving autonomous vehicles to simplify and expedite the process of compensating victims.

These issues give rise to complex dilemmas regarding the allocation of responsibility among the driver, developer, and manufacturer.

- The **driver** (or, more accurately, the system user) still bears some responsibility, particularly when using Level 3 systems. They must understand the system's capabilities and limitations, operate it only within the permitted ODD, and be prepared to promptly take control when prompted by the system or in unforeseen situations. Defining what it means to "be prepared" and what constitutes an acceptable reaction time remains a subject of debate and research.

- The **software and AI algorithm developer** is responsible for the reliability, safety, and accuracy of the system's decision-making. Proving the developer's fault in cases of complex software errors or unanticipated AI responses to rare scenarios poses a significant legal challenge.
- The **manufacturer** (Original Equipment Manufacturer, OEM) is responsible for integrating all components into a cohesive system, conducting proper testing and validation, ensuring compliance with regulatory requirements, and providing users with clear and comprehensive information about the system's operation. Often, the manufacturer serves as the primary entity liable to consumers under consumer protection and product liability laws. An important aspect is also the distribution of responsibility along the supply chain, as vehicle manufacturers heavily rely on components and software from third-party suppliers.

Resolving legal liability issues is absolutely essential for ensuring public acceptance, trust, and the economic viability of autonomous transport. While the 2020–2025 period was characterized by intensified discussions, research, and initial legislative steps (e.g., requirements for data storage), the development of comprehensive, fair, and internationally harmonized legal frameworks for liability remains a critical task for the coming years, requiring collaborative efforts from lawyers, engineers, insurers, manufacturers, and legislators.

4. Commercialization of Autonomous Transport

Following the discussion of technological advancements (Section 2) and the establishment of the regulatory framework (Section 3), the logical next step is to analyze the commercialization process of autonomous transport. The period from 2020 to 2025 witnessed a significant transition from predominantly research and demonstration projects to initial attempts at real commercial deployment of unmanned technologies across various economic sectors. While full-scale implementation remains a future prospect, these years laid the foundation for new business models and saw the emergence of the first services utilizing autonomous vehicles to provide solutions for consumers and businesses. This section examines the key areas of commercialization that gained momentum during this period.

4.1. Autonomous Taxis and Shared Mobility Services

One of the most anticipated and widely publicized areas of commercialization is the development of autonomous taxi services (robotaxis) and other forms of shared mobility using autonomous vehicles. The concept involves creating fleets of unmanned vehicles that can be summoned via a mobile app for urban trips, potentially offering a cheaper, safer, and more accessible alternative to traditional taxis with human drivers. During the 2020–2025 period, several companies moved beyond testing to launch limited commercial operations in real urban environments.

- **Waymo One**, a subsidiary of Alphabet (Google), is a pioneer in this field. Building on years of technological development, Waymo launched its commercial service, Waymo One, in 2018 in suburban Phoenix, Arizona. Between 2020 and 2025, the company significantly expanded its operations, initially offering fully driverless rides (without a safety driver) to the general public in Phoenix and later launching and scaling operations in San Francisco, California. By early 2025, Waymo was actively expanding its presence in other U.S. cities, such as Los Angeles and Austin. The company uses specially equipped vehicles (primarily electric Jaguar I-PACE and Chrysler Pacifica Hybrid minivans) and focuses on gradual, meticulous expansion of its operational zones (**Operational Design Domains, ODD**) after detailed mapping and validation.
- **Cruise**, backed by General Motors and Honda, was another major player in the U.S. robotaxi market. The company actively deployed its services in San Francisco, Austin, and Phoenix, also offering fully driverless rides. Cruise relied on modified electric Chevrolet Bolt vehicles and developed its own driverless shuttle, Origin, without traditional controls. However, in late 2023, the company faced a major crisis following a high-profile incident in San Francisco, leading to the suspension of all operations nationwide, revocation of licenses, leadership changes, and significant layoffs. This incident starkly highlighted the risks and challenges related to safety and public trust. As of April 2025, Cruise is undergoing restructuring and taking cautious steps toward resuming testing and, potentially, limited operations in select cities (e.g., Phoenix, Dallas), but under much stricter regulatory oversight and likely with safety drivers reinstated initially.
- **Baidu Apollo Go** is the leading robotaxi service in China. Leveraging its open-source Apollo platform, Baidu demonstrated remarkable growth during the 2020–2025 period. Apollo Go launched commercial or pilot services in dozens of Chinese cities, including megacities such as Beijing, Shanghai, Guangzhou, Shenzhen, Wuhan, and Chongqing. A significant milestone was obtaining permits for fully driverless commercial operations (without a safety driver onboard) in designated zones of certain cities (e.g., Wuhan, Chongqing, Beijing), positioning China as a global leader in this regard. The scale of Baidu Apollo Go's operations (fleet size and number of rides) significantly surpasses that of many Western competitors, reflecting strong government support and rapid local adoption of the technology.

The business models employed by these companies share common features but also exhibit certain differences. The primary model is **ride-hailing**, similar to Uber or Bolt, where users book trips through a mobile app and pay based on a tariff (typically dependent on distance and time). The key long-term advantage of this model lies in the potential **elimination of driver-related costs**, which account for a significant portion of traditional taxi operating expenses. However, during the 2020–2025 period, companies faced substantial costs related to research and development, procurement and outfitting of expensive autonomous vehicles, maintenance, creation and upkeep of high-definition maps, remote monitoring and support, and navigating regulatory hurdles.

Most leading players (**Waymo, Cruise, Baidu**) have opted for a model of **owning and operating their own fleets**, which requires significant capital investment. Alternative models, such as licensing technology to other operators or partnering with existing taxi platforms, have been less common in the robotaxi market but may gain traction in the future.

A notable feature of the business model at this stage is operation within clearly defined geographic zones (**geofencing**) and **Operational Design Domains (ODD)**. This means services are available only in specific city areas and under certain conditions (e.g., not during extreme weather). Expanding coverage requires substantial efforts in mapping, testing, and obtaining permits, which limits the speed of business scaling. Pricing strategies are often competitive with traditional taxis and sometimes subsidized to attract early adopters and gather real-world operational data. In the long term, data collected by autonomous vehicle fleets could become an additional revenue stream (e.g., for improving maps or analyzing traffic), but the primary focus remains on transportation services.

In conclusion, while the autonomous taxi and shared mobility sector demonstrated technical feasibility and made initial steps toward commercialization during the 2020–2025 period, it remains in an early stage of development. Achieving profitability and broad geographic accessibility continues to be a complex challenge, dependent on overcoming technological, regulatory, economic, and social barriers. The examples of Waymo, Cruise, and Baidu Apollo Go illustrate diverse strategies and development trajectories, while also highlighting the significant risks inherent in this innovative field, as evidenced by Cruise's experience.

4.2. Unmanned Delivery

Beyond passenger transport, another highly promising area of autonomous transport commercialization that saw significant development during the 2020–2025 period is unmanned cargo delivery. This segment encompasses a wide range of solutions, from small robots for last-mile delivery to large autonomous trucks for long-haul freight transport. The potential to optimize logistics chains, reduce costs, increase delivery speed, and address labor shortages (particularly for truck drivers) spurred substantial investments and innovations in this field.

Last-mile delivery using autonomous devices became a testing ground for numerous companies. The concept involves deploying small, often electric, robotic couriers to deliver goods (groceries, parcels, food) directly to consumers' doors, particularly in dense urban areas or enclosed territories (e.g., campuses, business parks).

- **Amazon Scout**: E-commerce giant Amazon actively tested its six-wheeled Scout delivery robots, designed to navigate sidewalks, in several U.S. cities starting in 2019. These robots, roughly the size of a small cooler, moved at pedestrian speeds. However, despite initial enthusiasm, Amazon decided to discontinue the Scout program and cease field testing in October 2022, redirecting resources to other projects. This decision underscored the economic and operational challenges of scaling such solutions, even for large corporations.

- **Nuro**, as previously mentioned (Sections 2.3, 3.2), focused on developing specialized road vehicles (R2, R3) rather than sidewalk robots. Their compact unmanned vehicles are designed exclusively for goods transport, with no space for drivers or passengers. During the 2020–2025 period, Nuro established partnerships with major retailers and delivery services (e.g., Kroger, Walmart, Domino's Pizza, 7-Eleven, Uber Eats) to conduct real deliveries in California, Arizona, and Texas. The company made significant progress in obtaining regulatory approvals for commercial operation on public roads and, as of early 2025, continues to develop and expand its operations.
- **Starship Technologies** emerged as a leader in the **sidewalk delivery robot** segment. Their small six-wheeled robots are actively used for delivering food and small goods on dozens of university campuses, corporate complexes, and select residential areas in the U.S., U.K., Estonia, and other countries. With a large fleet (thousands of robots) and extensive operational experience (millions of deliveries), Starship demonstrated the viability of its business model, which relies on partnerships with educational institutions, retailers, and delivery platforms. During the 2020–2025 period, the company continued to refine its robots and expand its geographic reach.

Thus, the last-mile unmanned delivery segment during 2020–2025 presented a mixed picture: alongside successful examples of scaling (Starship) and the development of specialized solutions (Nuro), there were also setbacks for ambitious projects (Amazon Scout). This reflects the high competition and challenges in achieving economic efficiency in this sector.

Another significant direction was the development of **autonomous trucks** for long-haul freight transport. The potential cost savings from automation in logistics are immense, considering expenses on fuel, driver wages, and the widespread driver shortage in many countries. The primary model developed during 2020–2025 involved Level 4 autonomous systems operating primarily on highways in a **hub-to-hub** mode. In this model, an autonomous truck transports goods between logistics centers (hubs) located near highways, while the first and last miles of the route (within cities or to final destinations) are handled by human drivers.

- **Embark Trucks** was among the first companies to enter this market, focusing on software development and providing autonomous freight services. The company conducted active testing and pilot projects with major shippers and carriers in the U.S. However, in early 2023, **Embark Trucks announced the cessation of operations** and laid off most of its staff, citing unfavorable market conditions and difficulties in securing further funding. Its assets were subsequently sold.

- **TuSimple** was also a leading player, achieving notable successes, including the world's first **fully autonomous truck trip** (without a safety driver) on a public road in Arizona in late 2021. The company secured partnerships with major carriers (e.g., UPS) and truck manufacturers (Navistar, though this partnership later faced challenges). However, between 2022 and 2024, **TuSimple encountered significant difficulties**: internal corporate conflicts, investigations by the U.S. Committee on Foreign Investment (CFIUS), funding issues leading to its delisting from Nasdaq in early 2024, and a strategic pivot toward Asian markets. As of April 2025, its future in the U.S. market remains uncertain.
- Despite the challenges faced by individual players, the autonomous freight sector remains active. Companies such as **Aurora Innovation** (with its Aurora Horizon division), **Kodiak Robotics**, and **Waymo Via** (Waymo's freight division, though its priorities may have shifted) continued to develop and test their technologies during the 2020–2025 period, forming partnerships with carriers and logistics companies.

In conclusion, the commercialization of unmanned cargo delivery during the 2020–2025 period progressed along two main trajectories. In last-mile delivery, there was a search for optimal solutions (sidewalk robots, specialized road vehicles) with mixed success. In long-haul freight transport, impressive technical capabilities were demonstrated, but the market faced significant turbulence and consolidation. Achieving widespread commercial deployment in both segments still requires addressing substantial technological, economic, and regulatory challenges. Nevertheless, the potential for transforming the logistics industry remains exceptionally high.

4.3. Infrastructure Readiness

The successful and widespread commercialization of autonomous transport, as discussed in the contexts of robotaxis and unmanned delivery (Sections 4.1, 4.2), depends not only on the sophistication of the vehicles and their control systems but also, to a significant extent, on the readiness of the surrounding infrastructure—both physical and digital. The period from 2020 to 2025 was marked by growing recognition of this interdependence and initial steps toward creating an environment conducive to the efficient and safe operation of autonomous vehicles. Key elements of this infrastructure readiness include **Smart City** approaches, the development of **V2X** and **5G** communication technologies, and the creation and maintenance of high-definition (**HD**) digital maps.

Smart City approaches involve the integration of information and communication technologies (ICT), the Internet of Things (IoT), and big data analytics into urban system management to enhance efficiency, sustainability, and quality of life for residents. Autonomous transport is considered an integral component of future "smart" mobility. In the context of infrastructure readiness, Smart City initiatives offer several advantages for unmanned vehicles:

- **Intelligent traffic management**: Systems that adaptively control traffic lights based on real-time traffic flows can interact with autonomous vehicles (via **Vehicle-to-Infrastructure, V2I**) by transmitting information about signal phases (**Signal Phase and Timing, SPaT**), optimizing movement and reducing congestion.
- **Centralized data platforms**: Collecting and analyzing data from various sources (road sensors, surveillance cameras, vehicles, public transport) enables the creation of a dynamic picture of the traffic environment, which can be shared with autonomous systems to enhance their situational awareness and decision-making.
- **Expanded sensor infrastructure**: Installing additional sensors (cameras, LiDAR, radars) at complex intersections, blind spots, or areas with heavy pedestrian traffic can provide autonomous vehicles with supplementary environmental data, improving safety.
- **Integrated planning**: Smart City concepts promote the consideration of autonomous mobility in conjunction with other transport modes and urban planning (e.g., dedicated lanes, multimodal transport hubs, infrastructure adaptations for delivery robots). During the 2020–2025 period, many cities worldwide—particularly in Singapore, South Korea, China, parts of Europe, and the U.S.—implemented pilot Smart City projects that included elements designed to support autonomous transport. However, creating a fully intelligent infrastructure on a city-wide scale remains a complex and long-term endeavor.

V2X (Vehicle-to-Everything) communication technologies are another critical component of infrastructure readiness. V2X enables vehicles to exchange information directly with each other (**Vehicle-to-Vehicle, V2V**), with road infrastructure (**Vehicle-to-Infrastructure, V2I**), with pedestrians and other vulnerable road users (**Vehicle-to-Pedestrian, V2P**), and with networks (**Vehicle-to-Network, V2N**). For autonomous vehicles, this offers several benefits:

- **Extended perception horizon**: Receiving information about hazards or road conditions beyond the line of sight of onboard sensors (e.g., a vehicle braking sharply around a corner, icy roads ahead, or approaching emergency vehicles).
- **Cooperative maneuverability**: Coordinating actions with other vehicles for safe and efficient maneuvers (e.g., forming truck convoys (**platooning**), synchronized intersection crossings, or assistance with lane changes).
- **Enhanced safety**: Early warnings about the presence of pedestrians or cyclists (if equipped with compatible devices) and information about traffic signal statuses. During the 2020–2025 period, there was ongoing debate regarding the choice of primary V2X standard: **DSRC** (based on Wi-Fi) or **C-V2X** (based on cellular networks). The **C-V2X** standard, particularly with the advancement of 5G, gained increasing global traction due to its potentially superior performance and integration with existing mobile infrastructure. Initial deployments of V2X systems on some roads and vehicles began, but widespread adoption requires mass implementation of the technology in both infrastructure and vehicles.

The rollout of 5G infrastructure is closely tied to the development of V2X (especially C-V2X) and is a critical enabler for autonomous transport. Fifth-generation networks offer significantly higher bandwidth, ultra-low latency, and the ability to connect numerous devices simultaneously. This is essential for:

- Reliable operation of C-V2X with real-time data exchange.
- Rapid updates of high-definition digital maps (HD maps), which can be data-intensive.
- Support for remote control (**teleoperation**) or assistance functions in complex scenarios.
- Efficient transmission of large volumes of data from vehicles (sensor data, log files) for analysis, AI training, and system improvement.
- Development of **edge computing**, enabling data processing closer to the vehicle to reduce latency.

Global deployment of 5G networks progressed actively during the 2020–2025 period, laying the technological foundation for many connected and autonomous vehicle services. However, as of April 2025, ensuring comprehensive and reliable 5G coverage, particularly outside major cities and along key transport corridors, remains an ongoing challenge.

Finally, **high-definition (HD) digital maps** are a fundamental component for the safe and reliable operation of autonomous systems at Level 3 and above. Unlike conventional navigation maps, HD maps provide highly detailed (centimeter-level accuracy) three-dimensional models of the static road environment, including precise lane geometry, locations of road signs, traffic lights, lane markings, curbs, and sometimes surface textures or other landmarks. Autonomous vehicles use these maps for:

- **Precise localization**: By comparing sensor data (LiDAR, cameras) with the map, a vehicle can determine its position with high accuracy.
- **Prediction**: Maps allow the system to anticipate upcoming features (e.g., curves, intersections, speed limits) even before they are within sensor range.
- **Route and maneuver planning**: Maps enable the system to plan safe and efficient trajectories.

Creating and maintaining HD maps is a complex task. During the 2020–2025 period, key challenges included the high cost and labor intensity of initial mapping for large areas and the need for continuous updates to reflect changes in the road environment (e.g., construction, new signs, altered markings). Developers increasingly adopted automated mapping techniques and crowdsourcing approaches, leveraging data from operational vehicles to detect changes and update maps. The HD map market during this period included major players (e.g., HERE, TomTom, Waymo, Mobileye with its REM technology) and numerous startups, but issues of format standardization and ensuring global coverage with up-to-date maps remain unresolved.

In summary, infrastructure readiness—encompassing Smart City elements, V2X and 5G communication networks, and high-definition digital maps—is an essential prerequisite for the successful commercialization and scaling of autonomous transport. While significant progress was made in the development and pilot implementation of these infrastructure components during the 2020–2025 period, their full integration and widespread deployment require further substantial investments and coordinated efforts from government authorities, telecommunications operators, technology companies, and the automotive industry.

5. Current Challenges

Despite significant progress in technology, legislation, and initial commercialization efforts detailed in previous sections, the path to widespread adoption of autonomous transport remains fraught with serious challenges. The 2020–2025 period not only showcased the potential of the technology but also highlighted a range of complex issues that extend beyond purely technical or economic considerations. These challenges encompass social, ethical, safety, and operational aspects, and overcoming them is a prerequisite for realizing the promises of autonomous mobility. This section focuses on analyzing the most pressing obstacles facing the industry as of early 2025.

5.1. Social and Ethical Aspects

The integration of any transformative technology into society inevitably raises social and ethical questions. In the case of autonomous transport, where control over a potentially dangerous object is transferred from humans to machines, these issues become particularly acute. They will largely determine the pace and nature of unmanned vehicle adoption, regardless of their technical sophistication.

Public acceptance is a critical factor for success. Without sufficient trust and willingness from the public to use autonomous vehicles, their mass adoption will be unattainable. During the 2020–2025 period, public attitudes toward this technology remained complex and often contradictory, influenced by several factors:

- **Safety concerns**: Despite the potential to reduce traffic accidents by eliminating human error, high-profile crashes involving vehicles with automated systems (even if these were lower-level systems like ADAS or incidents such as the 2023 Cruise case) significantly undermined trust. Fear of system failures, unpredictable behavior in complex situations, or vulnerability to cyberattacks remains a major barrier.
- **Lack of awareness and familiarity**: Many people still have limited understanding of how autonomous vehicles work, their actual capabilities, and their limitations. This can lead to both unwarranted skepticism and unrealistic expectations. Direct interaction with the technology (e.g., riding in a robotaxi) can positively influence perceptions, but as of April 2025, such opportunities remain available to only a small number of people in select cities worldwide.
- **Privacy and data security concerns**: Autonomous vehicles are equipped with numerous sensors (cameras, LiDAR, microphones) and continuously

collect vast amounts of data about their surroundings, routes, and passengers. This raises concerns about unauthorized access, potential surveillance, or commercial exploitation of data without user consent.

- **Fear of job losses**: The prospect of transport automation causes anxiety for millions employed in driving-related professions (taxi drivers, truck drivers, bus drivers, couriers). The fear of widespread unemployment in these sectors is a significant social factor influencing attitudes toward the technology.
- **Psychological loss of control**: For many, driving is associated with a sense of freedom and control. Relinquishing this control to a machine can cause psychological discomfort and resistance.

During the 2020–2025 period, developers and some government bodies made efforts to enhance public acceptance through public demonstrations, educational programs, publication of safety reports, and attempts to increase transparency about system operations. However, building sustained trust is clearly a long-term process that will depend heavily on the technology's impeccable performance in real-world operations.

Another profoundly complex issue is the development of **ethical algorithms** for autonomous vehicles, particularly in the context of so-called "trolley problem" dilemmas. Although such scenarios are extremely rare, an autonomous vehicle could theoretically face an unavoidable accident where any maneuver would cause harm. For example, should the system swerve onto a sidewalk to avoid a collision with a truck, even if pedestrians are present? Should it prioritize minimizing the total number of casualties or protecting the vehicle's passengers?

The classic "trolley problem" thought experiment (whether to switch a track to save five lives at the cost of one) vividly illustrates these ethical dilemmas. During the 2020–2025 period, these issues were actively debated in academic, engineering, and public circles, revealing several fundamental challenges:

1. **Lack of ethical consensus**: There is no universally accepted answer to how a vehicle should act in such hypothetical situations. Large-scale studies, such as MIT's "Moral Machine" experiment, demonstrated significant cultural differences in moral priorities across countries.
2. **Programming morality**: How can complex, context-dependent ethical principles be formalized into computer code? Who should be responsible for defining these "moral rules" for vehicles—engineers, philosophers, legislators, or society through some consensus mechanism?
3. **Transparency and explainability**: Should "ethical" algorithms be fully transparent and understandable to users and regulators? Modern deep learning systems often operate as "black boxes," complicating explanations of their decisions.
4. **Legal implications**: How should liability be assigned for harm caused by a pre-programmed "ethical" choice made by a machine?

In response to these challenges, the 2020–2025 period saw the emergence of initial ethical guidelines and principles for AI development in autonomous transport from various organizations and governments. These guidelines typically emphasize prioritizing human life, minimizing harm, adhering to traffic rules, and ensuring fairness but avoid providing specific instructions for resolving “trolley problem” scenarios. Developers primarily focus on preventing such situations by maximizing the reliability of perception, prediction, and planning systems to avoid the need for such tragic choices altogether.

Thus, social acceptance and addressing ethical dilemmas remain interconnected and critically important challenges on the path to an autonomous future. While awareness and the level of discourse on these issues grew significantly during 2020–2025, building public trust requires not only technological excellence but also transparency, accountability, and ongoing dialogue among all stakeholders. Finding universally accepted solutions for programming “ethics” into machines remains one of the most complex tasks of our time.

5.2. Safety and Cybersecurity

Alongside social and ethical considerations, ensuring **functional safety** and **cybersecurity** of autonomous vehicles remains a fundamental challenge that directly impacts public trust and the feasibility of mass adoption. As automation levels increase, vehicles rely more heavily on complex electronic systems, software, and external connectivity. This not only raises the bar for system reliability but also introduces new vectors for potential malicious attacks. The 2020–2025 period was marked by growing awareness of these risks and intensified efforts to develop and implement relevant standards and practices.

Cybersecurity risks (hacker attacks) emerged as a key concern for connected and autonomous vehicles. A modern vehicle is essentially a sophisticated computer network on wheels, comprising dozens of **Electronic Control Units (ECUs)**, hundreds of millions of lines of code, numerous sensors, and various communication interfaces (cellular, Wi-Fi, Bluetooth, V2X, diagnostic ports). Each of these components could potentially serve as an entry point for malicious actors. The consequences of a successful cyberattack on an autonomous vehicle could be catastrophic:

1. **Compromised safety**: Remote takeover of critical functions—steering, braking, or acceleration—to cause an accident.
2. **Denial of service**: Disrupting the vehicle’s operation or critical systems.
3. **Data theft**: Stealing passengers’ personal data, location information, camera or microphone recordings, or commercially sensitive technology data.
4. **Ransomware attacks**: Locking the vehicle or access to data with a ransom demand.
5. **Sensor manipulation**: Deliberately misleading perception systems by spoofing GPS signals, jamming radars or LiDAR, or presenting deceptive images to cameras (**sensor spoofing/jamming**).

6. **Fleet disruptions**: Coordinated attacks on fleet management systems for robotaxis or delivery robots.

While no high-profile cases of large-scale malicious attacks on autonomous vehicles in real-world operations were reported during 2020–2025, numerous studies and demonstrations by "white hat" hackers (security researchers) convincingly demonstrated the existence of such vulnerabilities. In response, the automotive industry and regulators accelerated efforts to implement comprehensive cybersecurity measures, including: adopting **Secure Software Development Lifecycle** practices, encrypting data and communication channels, implementing authentication and authorization mechanisms, deploying **Intrusion Detection Systems (IDS)**, providing regular **Over-the-Air (OTA)** software updates to patch vulnerabilities, using **Hardware Security Modules (HSMs)**, and conducting thorough **penetration testing**.

Parallel to cybersecurity, **functional safety**—the ability of a system to perform its functions correctly or transition to a safe state in the event of failures (hardware malfunctions or systematic software errors)—remains critically important. International standards play a pivotal role in this context.

- **ISO 26262 "Road Vehicles – Functional Safety"**: Although developed before the era of high-level automation, this standard remains foundational for ensuring the safety of electrical and electronic systems in vehicles. It establishes processes for the entire product lifecycle, including: **Hazard Analysis and Risk Assessment (HARA)**; defining **Automotive Safety Integrity Levels (ASIL: A, B, C, D)** to indicate required risk reduction levels; formulating **safety goals**; specifying requirements for hardware and software design; and methods for verification and validation. Applying ISO 26262 to complex autonomous driving systems, particularly those based on AI, presents new challenges related to nondeterministic behavior and the difficulty of comprehensive testing. These challenges are partially addressed in supplementary standards like **ISO/PAS 21448 (SOTIF – Safety of the Intended Functionality)**, which focuses on safety issues arising from functional limitations in the absence of faults (e.g., insufficient sensor performance under certain conditions).
- **ISO/SAE 21434 "Road Vehicles – Cybersecurity Engineering"**: Published in 2021, this standard became a response to growing cyber threats and gained particular relevance during the 2020–2025 period. It establishes uniform requirements and processes for ensuring cybersecurity throughout a vehicle's lifecycle—from conception to decommissioning. ISO/SAE 21434 mandates organizations to implement a **Cybersecurity Management System**, conduct **Threat Analysis and Risk Assessment (TARA)**, define cybersecurity goals, implement appropriate protective measures at the product and process levels, and verify and validate their effectiveness. Notably, this standard is closely linked to ISO 26262, as cybersecurity is often a prerequisite for functional safety (e.g., protection

against unauthorized interference that could lead to unsafe behavior). Additionally, new UNECE regulations, particularly **UN Regulation No. 155** on **Cybersecurity Management Systems (CSMS)**, which took effect in signatory countries (including the EU) between 2022 and 2024, require manufacturers to demonstrate compliance with requirements similar to those in ISO/SAE 21434 to obtain vehicle type approval.

In conclusion, ensuring functional safety and robust cybersecurity is an integral and critically important task in developing reliable and safe autonomous vehicles. The 2020–2025 period was marked by the formalization of requirements and standards in these areas (notably with the introduction of ISO/SAE 21434 and UNECE regulations). However, given the continuous evolution of cyber threats and the increasing complexity of autonomous systems, maintaining a high level of safety and security requires ongoing efforts, investments, and vigilance from all participants in the automotive ecosystem. These challenges remain at the forefront of developers' and regulators' attention as of April 2025.

5.3. Labor Market Adaptation Challenges

Beyond issues of safety, ethics, and public perception, one of the most significant socio-economic challenges arising from the development of autonomous transport during the 2020–2025 period is its potential impact on the labor market. The prospect of automating vehicle operation inevitably raises concerns about the future of millions of people worldwide whose livelihoods depend on driving-related professions. At the same time, this technological transformation creates demand for new skills and occupations, necessitating profound changes in education and professional training approaches.

Retraining drivers is a central aspect of this challenge. Automation threatens to significantly or entirely displace human labor in professions such as truck drivers (particularly for long-haul transport), taxi drivers, bus drivers, delivery couriers, and personal chauffeurs. The scale of potential workforce displacement is substantial, and many affected workers possess specialized skills that are not easily transferable to other economic sectors. While full automation (**Level 5**), which would render drivers obsolete in all conditions, remains a distant prospect for the mass market as of April 2025, the gradual adoption of higher automation levels (**Level 3 and 4** in specific domains) is already reshaping the role of drivers. For instance, in the **hub-to-hub** model for trucks, a driver's role may shift from continuous driving to monitoring systems on highways and operating only in complex "first/last mile" segments, or to roles as operators overseeing multiple vehicles. This requires new competencies related to interacting with and maintaining automated systems.

Recognition of these challenges prompted discussions and the development of initial strategies to mitigate impacts during the 2020–2025 period. The need for **proactive measures** became increasingly evident, including:

1. Developing and funding government programs for **retraining and upskilling** transport industry workers at risk of job loss, focusing on acquiring skills in demand in new or related economic sectors.

2. Defining **the role and responsibility of the industry** (technology developers, vehicle manufacturers, logistics companies) in supporting workforce adaptation.

3. **Modernizing vocational and higher education systems** to prepare professionals for working with new technologies, including skills in maintaining autonomous systems, managing mixed traffic flows, and analyzing data.

However, the effectiveness of retraining programs depends on several factors: accurate forecasting of future labor market demand, the quality and accessibility of training programs, and workers' motivation. Ensuring a **just transition** for millions of drivers remains a complex task requiring coordinated efforts from governments, businesses, and educational institutions.

Conversely, the development of autonomous transport not only eliminates existing jobs but also **creates new professions and specializations**, a trend that became more pronounced during the 2020–2025 period. Emerging or expanding fields of employment include:

- **Fleet operators and dispatchers** for autonomous vehicles: Professionals who remotely monitor unmanned vehicle operations, provide assistance in non-standard situations (teleoperation), and manage logistics and scheduling for robotaxi or delivery robot fleets.
- **Technicians for autonomous systems**: Highly skilled specialists capable of diagnosing, repairing, and maintaining complex autonomous vehicle equipment, including sensors (LiDAR, radars, cameras), computing platforms, actuators, and software.
- **Data analysts and machine learning specialists**: Experts needed to process and analyze vast datasets generated by autonomous vehicles, improve AI algorithms, and perform data labeling for training neural networks.
- **Developers and engineers of high-definition (HD) maps**: Specialists tasked with creating, validating, and continuously updating detailed digital maps essential for autonomous system navigation.
- **Cybersecurity experts**: Professionals developing and implementing solutions to protect autonomous vehicles and related infrastructure from cyberattacks.
- **User interface and experience (UX/UI) designers**: Specialists designing intuitive and safe human-machine interaction methods for autonomous systems.
- **Urban planners and mobility management experts**: Professionals integrating autonomous transport into city transport systems, developing relevant infrastructure, and shaping policies.
- **Legal and ethics specialists**: Experts addressing the legal, regulatory, and ethical aspects of developing and deploying autonomous technologies.

Notably, many of these new professions require higher qualifications, technical education, and specialized knowledge, potentially creating a **skills gap** compared to traditional driving roles. Whether the creation of new jobs will offset potential losses remains an open question and a subject of economic research and forecasting.

In conclusion, adapting the labor market to the era of autonomous transport is one of the most critical socio-economic challenges. The 2020–2025 period highlighted both the scale of potential disruptions to traditional professions and the range of new opportunities. Successfully managing this transition will require comprehensive and proactive strategies for retraining, education reform, and social support to maximize the benefits of technological progress while minimizing its adverse societal impacts.

6. Prospects for Implementation

The analysis of technological advancements, regulatory changes, initial commercialization steps, and current challenges presented in previous sections enables the outlining of potential trajectories for the further development and implementation of autonomous transport. While precise forecasting of the future is inherently challenging, especially in such a dynamic field, current trends and an understanding of necessary prerequisites allow for the formulation of likely **scenarios for the 2025–2035 period** and the identification of key conditions for a mass transition to higher levels of autonomy.

The future of autonomous transport is unlikely to be uniform; different market segments (freight transport, public transport, personal vehicles, delivery) and regions of the world will likely progress at varying paces. Several main scenarios can be identified for the next decade:

1. **Gradual Evolution and Niche Dominance Scenario (Most Likely)**: This scenario envisions the continuation of current trends, with an emphasis on expanding the use of autonomous systems in clearly defined **Operational Design Domains (ODD)**.

   - **Autonomous freight transport**: Level 4 (L4) technologies for hub-to-hub long-haul transport will become increasingly common on key transport corridors in the U.S., Europe, and China, improving logistics efficiency and partially addressing driver shortages.
   - **Robotaxis and shuttles**: L4 services will expand their geographic coverage within specific cities, university campuses, and airports but will remain constrained by weather conditions, complex road scenarios, and the need for remote monitoring and support systems. Competition with traditional taxis will intensify, but complete displacement will not occur.
   - **Last-mile delivery**: The use of sidewalk robots (e.g., Starship) and specialized road vehicles (e.g., Nuro) will continue to grow in densely populated areas for goods and food delivery.
   - **Personal vehicles**: Advanced Driver Assistance Systems (ADAS) at Level 2/2+ will become standard in most new vehicles. Level 3 systems (advanced

ALKS with lane-changing capabilities and higher-speed operations) will gain traction in the premium segment, but widespread adoption will be limited by high costs, unresolved liability issues, and the requirement for drivers to remain ready to intervene. The emergence of affordable private Level 4/5 vehicles in significant numbers by 2035 is unlikely.

2. **Accelerated Deployment Scenario (Optimistic)**: This scenario is feasible with faster breakthroughs in key technologies (particularly AI handling of edge cases), significant cost reductions in sensors and computing platforms, and rapid international harmonization of regulations. In this case, broader availability of L4 robotaxi services in many major cities worldwide could transform urban transport markets. L4 autonomous freight transport could extend beyond simple highway routes. Initial L4 systems for personal vehicles, operating in specific ODDs (e.g., fully autonomous highway driving or automated parking), may emerge.

3. **Stagnation or Slowdown Scenario (Pessimistic)**: Development could stall due to several factors: major safety-related incidents undermining public trust, prolonged legal uncertainty regarding liability, economic downturns reducing investment in development and infrastructure, or insurmountable technical challenges (e.g., operation in extreme weather). In this scenario, companies may abandon ambitious L4/L5 goals and focus on refining Level 2/3 ADAS. Commercial applications would remain confined to narrow niches, with the industry potentially shifting focus to electrification and connectivity (V2X) rather than full automation.

As of April 2025, the gradual evolution scenario with active development of commercial Level 4 applications in controlled ODDs appears the most realistic, while achieving high levels of automation for personal transport in all conditions remains a more distant prospect.

Central to discussions of prospects are the **SAE automation levels**, particularly **L4** and **L5**:

- **Level 4 (High Automation)**: The system fully controls all aspects of driving within a clearly defined ODD (e.g., specific geographic area, road type, weather conditions, time of day). No human intervention is required within the ODD, and the system can safely transition to a safe state if it exceeds the ODD or encounters a failure. This level is the target for most current robotaxi and autonomous trucking services.
- **Level 5 (Full Automation)**: The system can perform all driving functions under any conditions (road or weather) that a human driver could handle, with no ODD restrictions. This is the ultimate goal of autonomous driving.

The **transition from L3 to L4 is a fundamental leap**, as L4 systems fully relieve humans of responsibility for monitoring the environment and intervening within the ODD. Achieving Level 5, however, is far more challenging than L4, requiring the system to operate safely everywhere and always, including the rarest and most unpredictable scenarios (the “long tail” of edge cases). This demands breakthroughs in AI, sensor technologies, and validation methods. Most experts agree that mass adoption of Level 5 systems by 2035 is unlikely. Efforts in the next decade will focus on expanding the capabilities and ODDs of Level 4 systems, enhancing their reliability, and reducing costs.

For a mass transition to higher autonomy levels, several key conditions spanning technological, political, and socio-cultural dimensions must be met:

1. **Technology**:
   - **Proven safety and reliability**: Demonstrating (with statistical evidence) a safety level significantly surpassing human drivers across diverse operating conditions, including solutions for reliable operation in extreme weather and handling unpredictable edge cases.
   - **Economic viability**: Significant cost reductions for key components (LiDAR, computing platforms) and overall autonomous systems to ensure affordability for the mass market, particularly for personal vehicles.
   - **Scalable solutions**: Developing efficient and cost-effective processes for creating and updating HD maps, validating software, managing large autonomous vehicle fleets, and maintaining them.
2. **Policy and Regulation**:
   - **Clear and harmonized legal frameworks**: Adopting clear, internationally aligned laws and regulations governing testing, certification, operation, and, crucially, liability for Level 4 and 5 systems.
   - **Standardization**: Establishing and implementing uniform standards for key technologies (V2X, data formats, safety testing methods, cybersecurity protocols).
   - **Infrastructure support**: Public and private investments in modernizing and building necessary infrastructure (5G coverage, V2I-equipped roads, potential dedicated lanes).
3. **Culture and Society**:
   - **Public trust and acceptance**: Overcoming fears and skepticism through demonstrated reliability, system transparency, educational campaigns, and positive user experiences, while addressing data protection and privacy concerns.
   - **Ethical consensus**: Achieving broader societal agreement or clear regulatory guidelines on decision-making principles for autonomous systems in ethically complex situations.
   - **Labor market adaptation**: Implementing effective support and retraining programs for workers whose jobs are threatened by automation.
   - **Behavioral shifts**: Adapting society to new mobility forms, increasing use of shared autonomous services, and rethinking attitudes toward car ownership and the act of travel.

In conclusion, the transition to an era of mass autonomous transport, particularly at Levels 4 and 5, is not merely a technological race but a complex, multifaceted transformation process. Realizing the promised benefits in safety, efficiency, and mobility accessibility by 2035 or beyond depends on synergistic progress across technology, policy, and public perception. While significant groundwork was laid by 2025, the next decade will be pivotal in overcoming remaining barriers and shaping the pace and contours of the autonomous mobility revolution.

Conclusions

The study, covering the dynamic development period of autonomous transport from 2020 to 2025, enables several overarching conclusions regarding achieved progress, current challenges, and prospects for further implementation of this transformative technology. This period marked a transition from predominantly experimental development to initial commercialization stages and the formation of a regulatory framework, highlighting both significant achievements and complex issues requiring resolution.

Summarizing technical, regulatory, and social progress, substantial advancements can be noted. In **the technological domain**, significant improvements were made in sensor systems (LiDAR, radars, cameras) and their integration into multi-sensor platforms (e.g., Tesla HW4, Mobileye SuperVision™, NVIDIA Drive Orin™-based systems), enhancing environmental perception reliability. The development of artificial intelligence algorithms, particularly deep learning, played a pivotal role in image recognition, behavior prediction, and decision-making. Extensive use of simulation environments (e.g., Waymo, Aurora) accelerated system training and validation. Initial steps were taken to improve system resilience in challenging weather and road conditions, though this remains a significant challenge.

In the regulatory domain, the 2020–2025 period was marked by key international initiatives, notably the adoption of **UN Regulation No. 157 (ALKS)**, the first legally binding document for Level 3 systems, and the development of the **ISO/SAE 21434** cybersecurity standard. Leading countries (U.S., EU, China, Japan) actively shaped national legislation to regulate testing and initial deployment, though approaches varied. Legal liability issues became a focus of intense debate, with universal solutions still elusive.

In **the social and commercial dimensions**, initial commercialization efforts emerged through robotaxi services (Waymo One, Baidu Apollo Go), unmanned delivery (Nuro, Starship), and autonomous freight transport pilots (TuSimple, Kodiak). These projects demonstrated technical feasibility but also revealed economic challenges and vulnerability to incidents (e.g., Cruise), impacting public perception. Discussions on ethical dilemmas, societal acceptance, and labor market impacts intensified.

Despite progress, **key challenges** remain substantial, including: ensuring absolute safety and reliability across diverse real-world conditions (the “edge case problem" and operation in adverse weather); high technology costs limiting mass adoption; lack of clear, harmonized international liability norms; ongoing cyberattack threats; insufficient public trust and acceptance; unresolved ethical issues; potential negative labor market impacts and the need for large-scale retraining; and inadequate digital and physical infrastructure (5G coverage, V2X, up-to-date HD maps).

These challenges define **key directions for future research**: developing more robust and reliable AI algorithms (including explainable AI, XAI); creating new sensor technologies and fusion methods; improving simulation, testing, and safety validation methodologies; exploring effective cybersecurity strategies; developing fair liability and insurance models; studying factors influencing public perception and trust; modeling socio-economic impacts and labor market adaptation mechanisms; and investigating effective human-machine interfaces (HMI).

Based on this analysis, the following **recommendations for autonomous transport implementation** can be formulated:

- **Policymakers and regulators**: Accelerate the development of clear liability legislation, promote international standards harmonization, invest in digital infrastructure (5G, V2X), support further research and pilot projects, and implement comprehensive workforce adaptation programs.
- **Industry stakeholders**: Prioritize safety and cybersecurity, enhance transparency about system capabilities and limitations, actively collaborate on standardization, adopt rigorous testing and validation methods, and engage in open dialogue with society and regulators.
- **Research community**: Focus on addressing key technological, ethical, and social challenges, fostering interdisciplinary collaboration for a holistic approach to autonomous mobility challenges.

The scope for further scientific inquiry in this field is vast, encompassing: in-depth studies on integrating autonomous transport into urban transport systems, including impacts on traffic flows, urban planning, interactions with conventional vehicles and pedestrians, and the development of **Mobility as a Service (MaaS)** based on autonomous fleets; specific focus on autonomous public transport (buses, shuttles), its economic viability, and social role; analysis of international standardization processes and the impact of regulatory differences on the global market; further exploration of cybersecurity resilience strategies; development of long-term socio-economic impact models; investigation of human factors in interacting with varying automation levels; and optimization of logistics networks using autonomous trucks and delivery robots.

In conclusion, autonomous transport undeniably has the potential to fundamentally reshape our understanding of mobility, enhancing road safety and transport efficiency. The 2020–2025 period demonstrated significant progress, but it also clearly delineated the complex challenges ahead. Further success will hinge on a balanced and responsible approach that integrates technological innovation, prudent policy, and consideration of societal needs and values. Only through the collective efforts of researchers, engineers, businesses, governments, and the public can the full benefits of autonomous mobility be realized in the next decade and beyond.

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