Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 128 **2025**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2025.128.12

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Pritom, N.D., Dey, N.L. Urban transformation through connected and automated vehicles: infrastructure, transportation, and societal impacts. *Scientific Journal of Silesian University of Technology. Series Transport*. 2025, **128**, 199-235. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2025.128.12

Nixon Deb PRITOM[1], **Nondon Lal DEY**[2]

URBAN TRANSFORMATION THROUGH CONNECTED AND AUTOMATED VEHICLES: INFRASTRUCTURE, TRANSPORTATION, AND SOCIETAL IMPACTS

Summary. The interconnected and self-driving vehicles (CAVs) are appearing in a world of human travel, where they promise enhanced safety, better efficiency, and a sustainable approach to transportation. But realizing their potential calls for a complete rethinking of today's infrastructure and CAVs' place in it. The research needed for that understanding to happen is very much in its early stages. This article serves as a beginning point for a full-scale study of the issue. It looks at the infrastructure changes that will be required to safely integrate CAVs into our lives, changes that already face several very serious obstacles. It also looks at the future societal and governmental changes the CAVs will force upon us. And it considers all these changes in light of what's become an essential landscape for the CAVs: the cybersecurity threat to the millions of lines of code the vehicles rely upon for their safe functioning. At the end, we'll also flag some gaps in what's known so far and what those gaps could mean for a future informed by the knowledge of the past.
Keywords: connected and autonomous vehicles, transport infrastructure, intelligent transportation systems, urban planning, societal and policy infrastructure

[1] Department of Civil and Environmental Engineering, Shahjalal University of Science and Technology, Sylhet, 3130, Bangladesh. Email: nixon43@student.sust.edu. ORCID: https://orcid.org/0009-0005-5708-3833
[2] Department of Informatics, University of Louisiana at Lafayette, 04 East University Avenue, Lafayette, LA 70504, USA. Email: nondon.dey1@louisiana.edu. ORCID: https://orcid.org/0009-0008-4834-1230

1. INTRODUCTION

The integration of Connected and Autonomous Vehicles (CAVs) in the contemporary transportation system led to an unprecedented opportunity to revolutionize our movement, safety, efficiency, and sustainability. It is necessary for proper advancement in technologies as well as reevaluating the existing infrastructure [1]. Approximately 57% of the global population is aware of autonomous vehicles and open to using them, and the number of usages will rise to 33 million by 2040. The autonomous vehicle market is currently valued at $54 billion. For the sake of demonstration, Audi intends to invest $16 billion in this sector by 2023 [2, 3]. This transformative technology has great potential for reducing traffic accidents, enhancing quality of life, and providing efficiency in transportation systems [4]. Due to its influence in transportation, the academic and private sectors showed interest in this topic. However, previous research has examined the specific aspect of integrating CAV, such as sensor technology in urban planning. There is limited literature that connects physical and digital infrastructure, societal changes, and policy frameworks. Prior research has provided valuable insights into the integration of CAV.

[5] examined the environmental effects, data sharing strategies, and protective mechanisms for autonomous vehicles. Another research showed the positive effects of CAVs such as the reduction of distance enhances road capacity without increasing the delays, results in improved throughput. Additional advantages may include fewer emergency room visits, lower car insurance cost, and reduced staff needed for traffic enforcement strategies [6, 7]. [8] proposed a model that illustrates the wide-ranging effects of CAVs, but their analysis did not encompass policy and digital infrastructure or the government's role. [9], [10] and [11] provided international guidelines for autonomous vehicles (AV), public adaptations, and traffic management, but overlooked the broader societal and governmental involvements. There are some review articles focused more on less technical aspects and more on comfort and personalization [12, 13], but they tend to neglect the implementation concerns of road infrastructure. [14] and [15] evaluated the impact of AV on behavioral reasoning, urban life, reduced energy use, mitigating traffic congestion, safety, efficiency, and healthcare sector, and focused solely on shared autonomous vehicles. [16] presented a review, aiming at firms and financial performance of AV. We identified the most critical challenges related to the field of connected and automated vehicles, described in Table 1.

Tab. 1

Key Obstacles in the Development of Connected and Autonomous Vehicles

Domain	Obstacles
Technological	Sensor reliability, infrastructure connectivity, vehicle path modeling, wireless networks, geolocation precision, detailed urban mapping, high-speed data networks, and efficient data/resource management.
Societal	Accessibility, environmental impact, public health, ethical considerations, system costs, and digital literacy requirements.
Policy	Liability frameworks, harmonization of regional and national regulations, institutional expertise, inter-agency coordination, transition to smart mobility, operator training, and safety standards.

Additional Factors	Data security, urban space allocation, adoption rates, infrastructure design, signage updates, road markings, adaptive speed regulations, and balancing current transportation maintenance with future-oriented investments.

The existing literature lacks comprehensive information on how diverse aspects of CAVs, such as infrastructure, regulation, and society, are interconnected, apart from the aforementioned works. This paper aims to fill this gap by providing a holistic analysis of the infrastructure requirements essential for the safe and efficient adoption of CAVs. Therefore, we propose a network graph that highlights the connection between these topics, as seen in Figure 1.

This figure summarizes the infrastructure requirements for CAV integration, and is structured into four interconnected domains: physical infrastructure, digital infrastructure, public sector involvement, and urban planning and societal impact. Each domain is further subdivided into specific thematic areas, reflecting the multifaceted nature of this challenge. While these areas are interconnected, the degree of interdependence varies. For instance, the subject Roadway Adaptations for Mixed Traffic (the first topic in blue) significantly influences aspects of the physical infrastructure domain and has partial connections to certain digital infrastructure components but has limited direct links to public sector policies or urban planning considerations.

Additionally, to enhance clarity and understanding, each thematic area is addressed in a dedicated section, beginning with a concise statement (in italics) specifying its interconnections with other topics within the framework. This organizational structure facilitates a clear and efficient understanding of the complex interplay between these various factors in the successful integration of CAVs.

Furthermore, we examine how these areas are interconnected and propose actionable solutions to address the challenges they present. By synthesizing existing knowledge and offering new insights, this paper highlights the importance of interdisciplinary collaboration and strategic planning to facilitate the transition to a CAV-dominated future. The main novelty of this work is to provide an integrated discussion about the challenges that need to be confronted to promote proper implementation, which has not been thoroughly discussed in the literature, and the contributions of this paper are threefold:

i. We provide a comprehensive synthesis of existing knowledge on CAV infrastructure challenges, highlighting the interconnected nature of physical, digital, policy-related, and societal issues.
ii. We identify critical gaps in current research and propose actionable solutions to address these challenges.
iii. We offer future research directions to guide the development of infrastructure that can support the widespread adoption of CAVs.

This work describes the necessary adaptations to physical infrastructure, encompassing roadway design, traffic management systems, and non-roadway elements like parking and charging facilities in Section 2. Section 3 explores the complexities of digital infrastructure requirements, including Roadside Units (RSUs), communication networks, high-definition (HD) maps, and data management challenges. Section 4 examines the role of the public sector in facilitating vehicular transition through planning, partnerships, and regulatory frameworks. Section 5 explores the broader impacts of these new vehicles on urban planning, societal dynamics, and equitable access to the benefits of this transformative technology. After exploring each topic separately, in Section 6 we discuss how these topics are interconnected and affect each other. Finally, in Section 7 we present the conclusion and recommendations for future research.

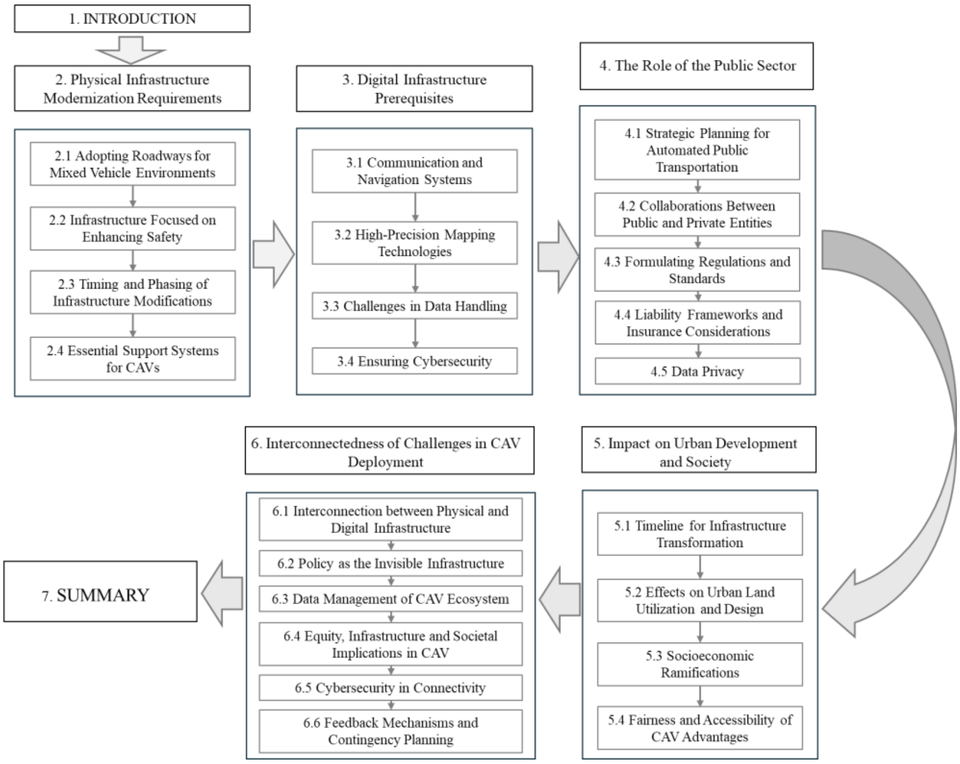

Fig. 1. Flowchart of the study

2. PHYSICAL INFRASTRUCTURE MODERNIZATION REQUIREMENTS

The widespread integration of CAVs necessitates updates to the existing transportation infrastructure. Roadways designed for human drivers must evolve to accommodate the unique capabilities of CAVs while prioritizing the safety of all road users, including pedestrians and cyclists. Several challenges exist in implementing the necessary adaptations to current transportation infrastructure to ensure safe and efficient coexistence with conventional vehicles, pedestrians, and cyclists. This section will therefore discuss the required modifications to physical infrastructure elements (roadway and non-roadway), particularly focusing on safety, while considering the strategic planning needed for a smooth rollout of automated technology.

2.1 Adapting Roadways for Mixed Vehicle Environments

This section tends to interact with the Safety Focused Infrastructure, Timing Infrastructure Changes, Communication and Navigation, High-Definition Maps, and Planning for Automated Transits. CAVs must coexist with human-driven vehicles during the transition periods, and there is a necessity of road infrastructure that supports both [17]. The existing road infrastructure faces significant challenges due to the integration of both at a time. When we talk about the synergized implementation of both connected and conventional vehicles, it is necessary to re-evaluate the traditional design elements such as geometric layout, markings and signage, and traffic signals to ensure safety and efficiency.

Geometric design elements require reevaluation in the mix-traffic environment. CAVs have faster reaction times than human drivers, which could allow for shorter stopping distances and might influence roadway curvature and other geometric design features [18, 19], while their precise vehicle control and potential for coordinated movement could allow for shorter following distances and potentially narrower lane widths, increasing road capacity in the existing streets, compared to current vehicles [20, 21]. However, given that automated vehicles have lane keeping capabilities, repeated loading and less wheel wander might increase pavement deterioration [22].

As CAV adoption increases, the necessity for exclusive lanes should be considered, balancing the potential for increased traffic flow and safety for automated vehicles with ensuring that conventional vehicles do not experience increased congestion [23-26]. Intersections pose unique challenges, and vehicle-to-infrastructure (V2I) communication could improve signal timing based on real-time presence and trajectories [27-29]. In the long term, with high penetration, dynamic slot-based intersection management could eliminate the need for traffic signals entirely, improving throughput if all vehicles are automated [30].

Ensuring clear visibility and legibility of road markings and signage for both human drivers and vehicles is crucial [31]. Marking and signage need standardization and rigorous maintenance for optimal detection by CAV machine vision systems [32]. Emphasis should be placed on machine-readability alongside visual clarity for human drivers, potentially through contrasting colors, clear delineations, and even embedded materials optimized for camera and Light Detection and Ranging (LiDAR) detection [33, 34].

2.2 Infrastructure Focused on Enhancing Safety

This section tends to connect with roadway adaptations for mixed-traffic, Timing Infrastructure Changes, CAV Support Infrastructure, High-Definition Maps, Cybersecurity, and Regulations and Standards Development. The condition of the road surface directly affects the safe and efficient operation of vehicles. Maintaining roads with high-friction, well-kept surfaces is important for reducing brake distances and preventing skidding [35]. Pavement inconsistencies cause variations in surface friction, which negatively impact CAVs' ability to accurately calculate safe operating parameters [36], especially in adverse weather conditions [37]. This reduced predictability of friction levels impairs the vehicle's algorithmic decision-making processes, potentially leading to errors in braking distance and increasing collision risks [38].

In addition to surface quality, embedded sensors in the road surface can further enhance vehicular safety by providing real-time vehicle monitoring and collecting data on road conditions and hazards like potholes, loose debris, or slippery conditions caused by rain or ice [37, 39]. With this data, vehicles can proactively adjust speed, direction, and braking to mitigate risks [31]. Furthermore, utilizing big data and artificial intelligence with sensor data enables predictive maintenance strategies [40], allowing road managers to identify potential deterioration patterns and prioritize maintenance actions to prevent infrastructure failures that could endanger passengers and other road users [41, 42]. This focus on well-maintained road infrastructure directly contributes to the safety benefits of improved visibility for CAVs, although more frequent maintenance will affect asset management strategies and infrastructure budgets.

Enhanced visibility is essential for CAVs to perceive their environment and provide direct safety benefits. Lighting improvements are important for infrastructure, especially at night when the performance of camera and LiDAR systems degrades [39]. Upgrading road lights with energy-efficient LEDs that offer higher brightness enhances visibility. Additionally, road markings using high retroreflectivity paint or materials significantly improve the effectiveness of sensors in detecting lane markings, signs, and crosswalks [43, 44], which is particularly important in adverse conditions such as rain or fog [38]. Moreover, implementing V2I communication capabilities enables dynamic real-time adjustments to roadway lighting, allowing infrastructure elements like streetlights to automatically increase brightness or change lighting angles based on a vehicle's presence and movement in a given area, further improving visibility while maintaining energy efficiency. These improved visual conditions enhance the accuracy of pedestrian and cyclist detection, a crucial aspect of CAV operation [45].

One of the main challenges for vehicles is to detect and proactively react to vulnerable road users (VRUs), mainly pedestrians and cyclists [46]. To ensure safety, limitations in existing sensors need to be overcome to accurately detect VRUs in various situations such as low light, weather interference, and scenarios where VRUs are partly hidden by other objects [47]. There are developments being made to expand the capabilities of sensors [48, 49], such as using thermal cameras that reliably detect VRUs in low-visibility situations and are less influenced by changing lighting conditions [50], or millimeter-wave radar systems that offer all-weather detection capabilities that complement traditional sensors. Additionally, the usage of LiDAR technology can provide advantages over cameras, such as higher resolution and broader field-of-view, resulting in better detection accuracy [51]. Furthermore, cooperative perception can bring improvements to VRU detection. Vehicle-to everything (V2X) communication enables a network connection where VRUs can carry small transponders that share their location data directly with vehicles [47]. In addition, roadside sensors improve VRU detection at intersections, providing the moving vehicle information that it would not be able to detect solely with its onboard sensors [52], significantly reducing blind spots and increasing the level of safety for mixed traffic situations.

The safe integration of CAVs into existing transportation systems requires strategic infrastructure adaptations, particularly at intersections and roundabouts. Dedicated lanes offer a practical solution for streamlining traffic flow and mitigating potential conflicts between automated and human-driven vehicles. Transforming traditional intersections into “smart intersections” equipped with sensor networks, intelligent cameras, and V2X communication technologies would be another way to improve safety significantly. These smart intersections enable dynamic traffic signal optimization, reducing congestion and enhancing safety for all road users. However, implementing infrastructure upgrades requires meticulous consideration of the timing and pace of changes, accounting for factors like vehicle adoption rates, technological maturity, and cost-benefit analysis.

2.3 Timing and Praising of Infrastructure Modifications

This section tends to connect with roadway adaptation for mixed traffic, Safety Focused Infrastructure, CAV Support Infrastructure, Data Management Issues, Planning for Automated Transit, and Infrastructure Transition Timeline. Infrastructure for CAVs needs to be updated with a careful balance between immediate changes and long term/large-scale investments [53]. Immediate changes aim to maximize the functionality of existing infrastructure to improve safety and efficiency in the near term. For instance, upgrading traffic lights with sensors or connecting them to central management systems can optimize signal timing [54]. This involves investments such as redesigning intersections with designated lanes and deploying RSUs along major routes. Establishing dedicated short-range communication networks enables the V2X communication needed for smooth traffic flow; this long-term vision is reflected in infrastructure research and recommendations [27].

The pace of infrastructure change will be closely related to the rate of CAV adoption [55]. A gradual increase in vehicle penetration will require a correspondingly measured and adaptive evolution of infrastructure, allowing continuous monitoring and evaluation, avoiding overinvestment in costly infrastructure that may remain underutilized if adoption falls behind predictions. On the contrary, early studies focused on autonomous vehicles alone, newer work emphasizes "connected and automated vehicles." Although vehicles can be automated without connectivity or connected without automation, connectivity is expected to significantly enhance automated vehicles soon [56]. Since the pace of adoption remains uncertain, flexible infrastructure planning and scenario-based responses by government agencies become critical [57]. Strategic planning in this context will directly influence asset management strategies, for example.

Effective asset management is important for strategically timing infrastructure upgrades. Immediate actions must align with long-term goals, ensuring initial improvements are compatible with future technologies and maximizing the lifespan of investments, while minimizing the risk of creating isolated assets that could become obsolete prematurely. Intelligent asset management uses data-driven analytics to identify optimal locations for initial upgrades and areas where traditional traffic management techniques can remain effective. A well-defined asset management plan streamlines transition costs, avoiding unnecessary renovations as CAV technology becomes more prevalent. This strategic approach extends beyond traditional road infrastructure and encompasses the development of comprehensive support infrastructure, as detailed in the following section.

2.4 Essential Support Systems for CAV’s

In addition to the challenges faced by road infrastructure, non-roadway infrastructure will also need to adapt to the increasing presence of automated vehicles. This includes parking facilities, maintenance depots, and charging stations for electric vehicles. As the demand for these new vehicles grows, there will be a need to expand and optimize non-roadway infrastructure to support the operational needs of these vehicles. This may involve the development of advanced charging infrastructure to cater to the increasing number of electric CAVs, as well as the implementation of smart technologies in parking facilities to accommodate vehicles with automated parking capabilities.

One of the key considerations is the provision of adequate parking facilities for these vehicles. As they are expected to change travel patterns and reduce the need for long-term parking in city centers, there will be an increased demand for short-term parking and drop-off zones. This shift in parking demand will require a re-evaluation of the parking facilities’ design and location to ensure that they are optimally situated to support operations [58].

In addition to parking, assuming the vehicles will be electric, the widespread adoption of CAVs will demand the development of an extensive electric vehicle charging infrastructure. The transition to electric and automated vehicles will require a significant expansion of charging stations to support the growing fleet. This infrastructure will need to be strategically located to enable seamless recharging [59] and to accommodate wireless and rapid charging technologies [60]. Furthermore, integration will also drive the need for smart charging infrastructure that can manage the demand for electricity and optimize charging schedules to minimize grid impacts and charging costs [61-63].

Moreover, the emergence of CAVs will impact the development of mobility hubs [64], envisioned as integrated transportation centers that provide seamless connectivity between connected vehicles, public transportation, and micromobility options [65]. Functioning as central transfer points, mobility hubs facilitate efficient transitions between modes, improving overall transportation efficiency and user experience. In addition to facilitating intermodal transfers, mobility hubs can offer amenities such as real-time travel information, integrated ticketing services, and secure bicycle storage [66]. The strategic implementation of these hubs can support the efficient and sustainable operation of CAVs within a multimodal transportation system, encouraging the use of shared and active transportation modes, improving accessibility, and reducing congestion and emissions.

Finally, their integration necessitates reassessment and enhancement of pedestrian facilities to prioritize the safety and accessibility of non-motorized transportation modes. As these vehicles are programmed to prioritize pedestrian safety, existing pedestrian infrastructure, including crosswalks [67], sidewalks, and shared spaces, requires reevaluation and redesign to improve interactions between vehicles and pedestrians. This may involve incorporating advanced sensing technologies, intelligent lighting systems, and clear visual cues to ensure pedestrian visibility and safety in the presence of automated vehicles. Additionally, the development of CAV-specific pedestrian infrastructure, such as dedicated drop-off and pick-up zones, is beneficial for seamless vehicular integration into the urban environment. These dedicated zones can enhance pedestrian flow, minimize potential conflicts between CAVs and pedestrians, and contribute to the creation of pedestrian-friendly and accessible urban spaces [68].

This shift towards a CAV-integrated transportation environment necessitates not only physical infrastructure adaptations but also a robust digital infrastructure to support seamless communication, navigation, and data management. In the following section we explore these challenges and what is required to enable safe and efficient operation [69].

3. DIGITAL INFRASTRUCTURE PRERESQUISITES

There are unprecedented complexities within the digital infrastructure framework when we talk about the integration of Connected and Autonomous Vehicles (CAVs) into existing transportation networks. Prior to the implementation and effective functioning, a robust and high-security network must be established to enable critical data exchange vehicles and their surrounding environment. So, it is essential to develop enhanced communication infrastructure integrating rigorous cybersecurity protocols so that it can ensure both operational safety and efficiency of CAV systems. Moreover, advanced vehicles generated a massive amount of data which proves the need for sophisticated digital infrastructure and analytical capabilities. When properly harnessed, this wealth of information can significantly enhance the performance of transportation systems, optimize vehicle operation, and unlock the transformative potential that lies in CAV technology. This section tends to examine the crucial elements that underpin the challenges. including the strategic deployment of Roadside Units (RSUs), advancements in cellular communication technology, requirements for precise navigation systems, comprehensive data management strategies, and imperative cybersecurity measures.

3.1 Communication and Navigation System

In the complex traffic environment, CAVs' communication architecture serves as the nervous system and enables their safety operation. For both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) information exchange, Roadside Units function (RSU) serves as a vital communication node [70-72]. These units support an expansive range of safety applications that include potential collision warnings, real-time traffic signal data transmission, work zone notifications, and detection systems for vulnerable road users such as pedestrians and cyclists. Beyond safety functions, RSUs contribute significantly to efficiency improvements through enabling dynamic speed adjustments, intelligent traffic signal optimization based on vehicle presence, streamlined electronic toll collection processes, and instantaneous updates regarding parking availability [1, 73].

Deployment of RSUs is also a critical element in this ecosystem, targeting high traffic intersections, accident-prone areas, and locations with potential Global Positioning System (GPS) limitations like tunnels or urban canyons [74, 75]. They support safety applications such as collision warnings, traffic signal information, work zone alerts, and detection of vulnerable road users. Additionally, RSUs facilitate efficiency improvements through dynamic speed adjustments, optimized signal timing, electronic toll collection, and real-time parking updates [76, 77]. Hardware and software updates and security checks as regular maintenance are necessary to ensure ongoing reliability and security [78].

The ongoing evolution of 5G cellular network technology represents another critical advancement supporting CAV communication frameworks. Compared to previous cellular generations, 5G offers substantially reduced latency, dramatically increased bandwidth capacity, and enhanced network reliability [79, 80]. These improvements enable instantaneous transmission of complex sensor data, high- definition video streams, over-the-air software updates, and time-sensitive safety messages. Such capabilities allow CAVs to execute rapid decision-making processes and respond proactively to dynamic traffic conditions with unprecedented speed and precision [81, 82].

Despite these communication advances, accurate geolocation remains a persistent challenge for CAV systems, particularly since conventional GPS technologies frequently deliver suboptimal performance in dense urban environments or situations, where satellite signals encounter obstruction. To address this limitation, sensor fusion methodologies have emerged as essential solutions, integrating data from diverse sources including LiDAR sensors, optical cameras, inertial measurement units, and differential GPS systems to achieve substantially improved location accuracy [83-85]. High-definition mapping systems further enhance positioning capabilities by providing intricately detailed representations of roadway features and environmental landmarks, enabling precise lane-level positioning while simultaneously serving as a crucial redundancy layer for navigation systems [86, 87].

3.2 High-Precision Mapping Technologies

Modern high-definition (HD) maps transcend the capabilities of conventional navigation systems, creating virtual environments that precisely mirror real-world conditions. These sophisticated mapping systems deliver centimeter-accurate three-dimensional models incorporating minute details such as lane boundary markings, regulatory signage, curb positions, road surface conditions, stationary obstacles (including guardrails and traffic signal infrastructure), and even temporary elements like construction barriers or lane modifications.

This comprehensive environmental representation provides CAVs with several critical operational advantages.

Perhaps most fundamentally, HD maps facilitate precise vehicle localization, particularly valuable during scenarios with compromised GPS reliability. Vehicles equipped with these systems can achieve accurate positioning by comparing real-time sensor observations against the detailed environmental features documented within their mapping databases, as discussed in the previous section. Additionally, these maps play an instrumental role in sophisticated path planning and trajectory generation algorithms. Comprehensive knowledge regarding upcoming road geometry, elevation changes, lane transitions, intersection configurations, and posted speed restrictions allows CAVs to develop proactive routing strategies while generating optimized vehicle trajectories characterized by both safety and passenger comfort.

The detailed environmental context provided by HD maps significantly enhances the object recognition and classification capabilities of onboard vehicle sensors. Furthermore, by incorporating regulatory expectations associated with traffic control devices—such as required vehicle stopping behavior at stop signs, these mapping systems augment the vehicle's ability to anticipate the likely movements of surrounding road users, improving predictive accuracy.

Maintaining both accuracy and currency within HD maps presents substantial logistical challenges for CAV deployment. Road networks exist in constant flux, with factors including construction activities, infrastructure maintenance, traffic incidents, temporary regulatory changes, and environmental disruptions from severe weather potentially altering driving conditions with minimal notice. Traditional mapping methodologies, which typically employ specialized survey vehicles and require weeks or months for complete implementation, cannot adequately address the dynamic nature of these environments. Consequent discrepancies between mapped representations and actual roadway conditions can potentially introduce decision-making delays as vehicle systems attempt to reconcile conflicting information sources. This reality underscores the urgent requirement for innovative real-time mapping solutions capable of ensuring HD maps accurately reflect the actual conditions CAVs will encounter during operation. The following Table 2 provides the information of major HD map companies, including background, technology, market reach, and unique features [88-90].

Many of these companies were found having a core business different from maps, such as NVIDIA (computer graphics), TomTom (software), and Woven (automotive research), others came from paper maps (Zenrin) or digital maps, such as HERE, Mapbox, Navinfo and OpenStreetMap. Companies such as Baidu Apollo, Mobileye, and Waymo were founded to develop driverless vehicles, consequently needing HD maps. Additionally, these companies are not necessarily competitors since many of them work and develop solutions together. Also, for example, Intel (a technology company), owns a large part of Mobileye and a smaller part of HERE.

CAVs themselves, equipped with their array of sensors, could be a significant part of the solution, acting as mobile data collection units for real-time map updates. Using a crowdsourcing approach, they could constantly collect and share data about road changes, construction areas, temporary obstacles, and other dynamic elements [91]. This vast and decentralized stream of information enables the potential for near real-time map updates, providing the most current representation of surroundings. However, crowdsourced map updates introduce challenges, such as ensuring the accuracy and reliability of sensor data from diverse vehicles and manufacturers, requiring rigorous data validation and quality control mechanisms. Additionally, managing the massive datasets generated continuously demands sophisticated data processing and storage solutions [81]. Finally, the seamless integration of data from various sources and sensors into the existing HD map is crucial for maintaining a cohesive and accurate representation of the road environment.

Tab. 2

Major HD map companies

Company (Country, Year founded)	Available to other companies ?	Free?	Details
Baidu Apollo (China, 2019)	Yes	Yes	Baidu is a leader in China's HD map sector, supporting its own robotaxi service and offering an open autonomous driving platform. Baidu Maps achieved national approval for advanced assisted driving maps in 134 cities, covering nearly 1.5 million kilometers. Its HD maps leverage AI for rapid, minute-level updates and integrate with Beidou high-precision positioning. Lane-level navigation and real-time emergency guidance are available in major cities.
Civil Maps (USA, 2015)	Yes	No	Civil Maps, acquired by Luminar in 2023, specializes in scalable, lightweight HD maps and localization solutions with 15–20 cm absolute accuracy. Their technology enables city-scale mapping and robust, real-time localization, serving AVs and sidewalk robots. Offices in the US, Europe, and Asia.
HERE (Netherlands, 1985)	Yes	No	HERE offers HD Live Map, a cloud-based, continuously updated mapping platform with global coverage. Their solution features road and lane-level data, localization support, and rapid map updates using AI-driven automation. HERE's UniMap technology enables fast, automated map creation and updating, supporting automotive OEMs worldwide.
Mapbox (USA, 2010)	Yes	No	Mapbox provides customizable, developer-focused location and mapping services. While not exclusively HD maps for AVs, their platform supports high flexibility and integration for various mobility applications. Used by automakers, ride-hailing, and logistics firms.
Mobileye (Israel, 1999)	Yes	No	Now owned by Intel, Mobileye offers lightweight HD maps (Road Experience Management, REM) that do not require 5G connectivity. Their maps are crowdsourced from production vehicles, enabling rapid scaling and frequent updates. Mobileye's technology is widely adopted by global automotive manufacturers.

Navinfo (China, 2002)	Yes	No	NavInfo is a leading Chinese provider of digital and HD maps, focusing on cloud-based services and high-precision data for autonomous driving. Core business includes automotive navigation, telematics, and smart mobility solutions.
Nvidia (USA, 1993)	Yes	No	Nvidia's DRIVE Map, launched in 2022, is a global mapping platform for self-driving cars. It integrates AI, crowdsourced data, and sensor fusion for centimeter-level accuracy. Nvidia collaborates with OEMs and AV developers worldwide.
OpenStreetMap (UK, 2004)	Yes	Yes	OpenStreetMap is a free, open-source, crowdsourced geographic database. While not natively HD, its data can be transformed into HD maps (e.g., OpenDRIVE) for AV research and development. Widely used in academia and open-source projects.
TomTom (Netherlands, 1991)	Yes	No	TomTom is a pioneer in HD mapping, releasing the first commercial HD map in 2015. Their maps are used in over 10 million vehicles globally and provide real-time updates for lane-level navigation and ADAS features. TomTom partners with major automakers and AV developers.
Waymo (USA, 2009)	No		Waymo, a Google subsidiary, develops proprietary HD maps exclusively for its robotaxi fleet. Its mapping data is collected via its own vehicles and is not licensed to third parties. However, Waymo offers open datasets for academic research.
Woven (Japan, 2018)	No		Woven, a Toyota subsidiary, focuses on automated driving R&D, vehicle OS, and mobility solutions. Its HD maps are developed in-house for Toyota's AV initiatives and are not commercially available.
Zenrin (Japan, 1948)	Yes	No	Zenrin is Japan's leading map provider, with HD maps covering all highways. Their maps are used by Japanese automakers and AV developers, supporting both navigation and advanced driver assistance systems.

3.3 Challenges in Data Handling

The operational backbone of Connected and Autonomous Vehicles (CAVs) lies in their ability to generate, process, and act upon vast quantities of data. A single vehicle can produce terabytes of information daily from LiDAR, cameras, GPS, and vehicle-to-everything (V2X) communications – far exceeding the capacity of traditional data systems [92-94]. This deluge necessitates scalable cloud infrastructure and edge computing solutions to balance real-time processing for safety-critical decisions (e.g., collision avoidance) with long-term storage for predictive analytics and system optimization. For instance, edge computing reduces latency by processing data locally, enabling split-second responses to dynamic road conditions, while cloud systems aggregate historical data to refine navigation algorithms [91, 95].

A persistent hurdle is the lack of standardization across manufacturers. Data formats vary widely – image resolutions from cameras, LiDAR point cloud densities, and telemetry sampling rates differ between brands – creating interoperability issues. Collaborative initiatives like the Society of Automotive Engineers (SAE) J2735 standard aim to unify V2X messaging, but gaps remain [96, 97]. Advanced data fusion techniques, which integrate inputs from disparate sensors (e.g., aligning LiDAR scans with camera feeds), are critical to creating coherent environmental models. These algorithms not only improve object detection but also enable cross-vehicle data sharing, a necessity for fleet learning and coordinated traffic management [91, 95].

Data ownership further complicates the landscape. Who controls vehicular data—owners, manufacturers, or municipalities? This question has legal, ethical, and economic dimensions. For example, automakers argue that telemetry data (e.g., engine performance) is proprietary, while urban planners seek access to traffic patterns for infrastructure upgrades [98, 99]. The European Union's Data Act (2023) attempts to mediate such conflicts by defining data-sharing obligations, but global consensus is lacking. Transparent governance frameworks are urgently needed to clarify rights, responsibilities, and safeguards across the data lifecycle—from collection to archival [100-102].

Privacy risks loom large. Detailed travel histories, when aggregated, can reveal personal habits, workplaces, and social networks. Technical measures like differential privacy (adding "noise" to datasets to anonymize individuals) and federated learning (training AI models on decentralized data) help mitigate exposure. However, procedural safeguards – such as user consent protocols and strict access controls – are equally vital. Public trust, a prerequisite for CAV adoption, hinges on demonstrable efforts to protect sensitive information [100, 103].

3.4 Ensuring Cybersecurity

The interconnected nature of CAVs – reliant on V2X networks, 5G, and cloud services [92, 96, 104] – creates a sprawling attack surface [105]. Threats range from benign hacking attempts to state-sponsored attacks aiming to disrupt urban mobility [104, 106]. For example, spoofing GPS signals could misdirect vehicles into unsafe routes, while jamming V2I communications might paralyze traffic signals at peak hours. Such vulnerabilities demand multilayered defenses, starting with quantum-resistant encryption for data in transit and homomorphic encryption for data at rest, ensuring confidentiality even if breaches occur [105, 106].

Sensors, the "eyes" of CAVs, are themselves targets. Researchers have demonstrated adversarial attacks where subtle stickers on stop signs confuse object recognition systems, causing misclassification. Countermeasures include sensor redundancy (e.g., cross-verifying LiDAR and camera inputs) and anomaly detection algorithms that flag inconsistent data streams. Toyota's recent partnership with Palo Alto Networks exemplifies industry efforts to embed security at the hardware level, isolating critical systems from less secure infotainment networks [107-109].

HD maps contain detailed data about road networks, which are essential for CAV decision-making. However, malicious actors might target this sensitive data, especially in crowdsourced maps, such as OpenStreetMap, Google Maps, and Waze. Modifying map data, such as changing road signs, traffic control information, or lane markings, could potentially misguide vehicles into performing incorrect or dangerous actions with the potential to cause accidents. Secure storage and transmission of HD maps, along with methods to ensure map integrity and authenticity, are necessary. Techniques such as digital signatures and verification of map updates against a trusted source may help detect unauthorized modifications [110]. There are already some tools to prevent this: new editions on Google and Waze must pass verification by experienced editors or employees; OSM editors have innumerous tools to verify vandalism [111], while Meta provides periodic OSM data snapshots that include fixes for vandalism and known errors in the OSM database.

Protecting the vehicular ecosystem against evolving threats requires comprehensive cybersecurity countermeasures. Encryption of data, both at rest (when stored) and in transit (during communication), is used to protect the confidentiality of communication and sensitive map data. Intrusion detection systems may be needed for network monitoring to detect anomalous activity that would indicate attempted attacks. Authentication mechanisms, that verify the identity of the sender and receiver in communication systems, ensure that CAVs and infrastructure components only trust data from authorized sources [112].

The cybersecurity of CAVs is a constantly evolving challenge, as new technologies and communication systems create new opportunities for attackers. To ensure safety and reliability, research and development to identify and mitigate potential vulnerabilities are needed. This involves updating threat models, testing vehicular systems proactively, and promoting a security-aware culture among all stakeholders involved in CAV deployment [113]. The complexity and interdependence of CAV technology require a collaborative approach to cybersecurity, where the public sector plays a key role in bringing together policymakers, manufacturers, technology providers, and researchers to develop inclusive cybersecurity solutions.

Key Themes for Policy & Industry:

- Collaborative Defense: Shared threat intelligence platforms, akin to the Automotive ISAC, enable manufacturers to pool resources against emerging risks.
- Ethical Hacking: Proactive penetration testing, as conducted by companies like Argus Cyber Security, identifies vulnerabilities before exploitation.
- Public Transparency: Disclosing breaches openly, as Tesla did in its 2024 Cybersecurity Report, builds credibility and accelerates industry-wide solutions [114, 115].

4. THE ROLE OF THE PUBLIC SECTOR

The transition to connected and autonomous vehicles (CAVs) demands more than technological innovation—it requires governments to reimagine their role as stewards of transportation systems. Municipalities and regulatory bodies must balance infrastructure modernization, ethical governance, and societal equity to ensure CAVs enhance—rather than disrupt – urban mobility. This involves crafting adaptive policies, fostering cross-sector collaboration, and addressing the socio-technical challenges inherent in deploying autonomous systems at scale.

4.1 Strategic Planning for Automated Public Transportation

Integrating CAVs into existing transit networks presents a paradox: while automation promises efficiency gains, its complexity risks exacerbating urban inequities if poorly managed [116]. A phased deployment strategy, prioritizing low-speed routes or geofenced urban zones, allows cities to test CAV safety and performance in controlled environments while minimizing public risk. For instance, pilot programs in university campuses or business districts – where traffic patterns are predictable and stakeholder buy-in is high – could serve as living labs for refining algorithms and infrastructure adaptations [117-119]. Such an approach not only mitigates technical targeting of underserved communities historically marginalized by conventional transit systems.

Policy frameworks must evolve to address CAVs' unique ethical and operational challenges. Traditional liability laws, designed for human drivers, falter when applied to algorithmic decision-making. Who bears responsibility when a CAV swerves to avoid a pedestrian but causes a collision? Regulatory updates should clarify liability thresholds, mandate independent safety certifications, and establish transparency requirements for AI-driven systems. The European Union's 2024 AI Act, which classifies CAVs as high-risk systems subject to rigorous auditing, offers a potential blueprint. Concurrently, public engagement initiatives—such as citizen advisory boards – can democratize the policymaking process, ensuring CAV deployment aligns with community values rather than corporate interests.

The public sector is responsible for shaping policy frameworks that mandate safety, address ethical dilemmas, and prioritize equity in the rollout of automated transit. Safety policies must establish strict performance standards and rigorous testing protocols for automated vehicles, potentially through independent certification processes [120]. Ethical considerations should focus on algorithmic transparency, addressing potential biases, and establishing clear protocols for vehicular decision-making. For instance, public input and the formation of ethics advisory boards would be useful tools in this process [121]. In addition, it is very important to ensure everyone can use the new transportation systems, especially people with disabilities. This includes equal access to technology and making the systems fair and helpful for people with different backgrounds and incomes.

Existing regulations governing vehicle licensing, operation, and liability are likely to require significant revision to accommodate automated transit. The public sector must proactively update laws and regulations addressing CAV technology. This includes establishing testing and certification requirements, potentially leveraging international standardization efforts where appropriate [122]. Updating regulations should also involve defining the scope of liability in accidents, licensing processes for CAV operators (if applicable), and insurance requirements uniquely tailored to their operation. Close collaboration with insurance providers and legal experts will be important to craft these regulatory updates.

4.2 Collaboration between Public and Private Entities

The creation and implementation of connected and automated vehicles is a sophisticated and multidimensional process that will benefit from a Public Private Partnership (PPP), which enables cooperation between public authorities, vehicle manufacturers, technology firms, and infrastructure providers. This cooperation facilitates the combination of resources, expertise, and risk-sharing, which are crucial for addressing the challenges related to the substantial investments and technological innovation required for CAV integration into transportation systems.

The success of PPPs in this sector depends on effective collaboration. Governments have an essential role to play in creating policy frameworks, ensuring safety standards, and regulating CAVs. Vehicle manufacturers and technology firms have expertise in vehicular design, sensor technology, and algorithm development. Infrastructure providers have important knowledge about traffic systems, road design, and sensor and communication network integration to support mixed traffic environments. Effective cooperation, with clear roles and responsibilities, enables innovation and speeds up the development of infrastructure suited for CAV operation.

A significant challenge in achieving widespread deployment is the need for large investment in both physical infrastructure upgrades and research and development. PPPs provide various investment models to address this challenge. These include joint ventures, where costs and risk are split; design-build- finance operate-maintain models, where private entities fund infrastructure development in return for operating rights; or concession agreements, where infrastructure assets are transferred to a private operator [123, 124]. Careful selection of the suitable PPP model, if deemed necessary, aligned with project scope and specific long-term goals, is required for maximizing the benefits of collaboration and ensuring stable funding mechanisms for the long lifespan of CAV projects.

PPPs can also support data sharing and standardization initiatives to develop interoperable systems that support smooth integration into transportation networks. The large datasets generated by these vehicles, including sensor data, driving behavior data, route data, and incident data, can be used to improve infrastructure design, traffic management, and safety analysis. However, there are several challenges that prevent the easy flow of data between companies and government entities.

A primary concern for companies, often motivated by competitive market forces, is the protection of proprietary data. The unwillingness to share datasets that are seen as valuable intellectual property and a source of competitive advantage impedes comprehensive system-level analysis [12, 126]. Additionally, public concerns about privacy must be addressed, given that connected vehicles raise questions about location tracking, the creation of individual profiles through data aggregation, and the potential for misuse of information [125]. Finding a balance between privacy protection and the benefits of data sharing is an ongoing challenge that both governments and companies could address through transparent data governance frameworks. The lack of universally adopted data-sharing formats and protocols creates interoperability barriers, as companies may have their own proprietary systems that do not easily integrate with government data platforms.

To encourage data cooperation, possible solutions include anonymizing and aggregating data to protect user privacy before sharing with external entities. Government incentives, such as financial subsidies, access to government-collected datasets, or simplified regulatory processes can be offered to companies showing a commitment to open data initiatives. Furthermore, the creation of independent institutions to define standards, implement anonymization procedures, and handle data exchange could act as trusted intermediaries between companies and governments [127].

4.3 Formulating Regulations and Standards

The creation of comprehensive and strong regulations and technical standards will help to ensure the safe, reliability, and ethical integration of CAVs into transportation systems. These regulations have multiple goals: setting consistent safety requirements, encouraging innovation through clear guidelines, and building public trust. Due to fundamental differences between traditional and automated vehicles, the public sector has a critical role to play in modifying existing regulations and creating entirely new frameworks tailored to the unique challenges and opportunities of automated operation.

Clear standards of safety and performance are the core of CAV regulation, which should include obstacle detection, collision avoidance, emergency protocol capabilities, decision-making in complex traffic scenarios, and safeguards against cybersecurity vulnerabilities [57]. While existing vehicle safety regulations provide a starting point, the distinctive capabilities and potential vulnerabilities of these vehicles require a novel regulatory structure.

The global nature of the automotive industry makes international cooperation for consistent vehicular standards essential. Initiatives by the United Nations Economic Commission for

Europe (UNECE) Working Party 29 [128], the International Organization for Standardization (ISO), and SAE International are creating common ground for communication protocols, data exchange, and testing procedures. These coordinated standards are important not only for ensuring the smooth cross-border movement of vehicles but also for promoting compatibility between different systems.

Additionally, the public sector needs to create rigorous testing and certification processes for both hardware and software components to ensure they meet or exceed mandated safety standards. This could involve a combination of simulation-based testing in virtual environments, controlled test-track evaluations, and progressive on-road deployment with strict safety protocols [129, 130]. The creation of third-party certification agencies could improve the objectivity of this process, providing validation for both regulators and the public. These certification processes must link directly back to the specific safety and performance standards established for CAVs.

Recognizing the fast pace of vehicular development, regulations need to be flexible and adaptable to accommodate technological innovations [131, 132]. It is important to have a regulatory framework designed to cope with ongoing review and updating, using real-world data, the latest research findings, and evolving technologies. Close collaboration between government agencies, research institutions, technology developers, and industry stakeholders would allow adaptable regulations to be created that support progress while prioritizing public safety.

4.4 Liability Frameworks and Insurance Considerations

A revision of traditional liability frameworks and insurance models may be necessary. Existing legal structures focus solely on the fault of drivers becoming inadequate when complex software algorithms, vehicle manufacturers and, potentially, infrastructure providers share responsibility for accidents or malfunctions. Public sector agencies are mostly responsible for modifying current liability laws, clarifying responsibilities, and ensuring comprehensive insurance solutions exist to protect all parties involved.

Traditional liability frameworks, based on negligent driver conduct, may fail to effectively address scenarios involving automated vehicles [57]. The question of liability will likely shift towards automakers, software developers, and even infrastructure operators, depending on the specific cause of accidents. Potential opportunities include changes to product liability laws or establish strict liability rules, where software flaws or hardware defects are automatically considered the liable party.

Insurance coverage will need to adapt to address the exclusive risks associated with CAVs and the evolving liability landscape. This could involve revised commercial liability policies for automakers and software companies, specific insurance products for automated taxis or ride-sharing fleets, and new models addressing cybersecurity threats unique to these vehicles [133]. Collaboration between insurance providers and policymakers will be critical in establishing risk assessment models and premiums that incentivize safe development and operation.

Some experts advocate for a shift toward no-fault insurance models in the context of CAVs [6]. These models simplify compensation for accidents while reducing the burden on courts to determine fault in complex cases involving multiple contributing factors. However, no-fault models raise questions about cost distribution, potential impacts on innovation, and ensuring individuals harmed by CAVs receive fair compensation.

4.5 Data Privacy

CAVs may require extensive data privacy regulations led by the public sector to protect individual privacy rights and foster public trust [100]. Determining data ownership, permissible use, and the implementation of strong security standards are essential to ensure transparency and responsible handling of information collected about vehicle movements, passengers, and their surroundings.

The ownership of data generated is a key issue. The vehicle owner, automaker, data processors, or government agencies might be able to claim it. Clarity on ownership (or no ownership at all [134]) can improve the establishment of individual rights to access, control, and potentially request deletion of their collected data. Informed consent mechanisms will likely be needed, providing users with transparent information regarding how their data is collected and utilized, enabling them to make choices about its use.

Robust regulations requiring secure data storage, encryption, and cybersecurity standards are important to prevent unauthorized access or breaches of sensitive information. Potential data breaches could endanger individual privacy or be used for malicious purposes, impacting public trust in CAV technology [135]. The public sector needs to establish strict cybersecurity protocols and potentially work with independent agencies to conduct audits and certifications of data handling practices.

Techniques for anonymization and aggregation offer ways to protect individual privacy while allowing the potential benefits of data analysis to be enjoyed in traffic management optimization and infrastructure planning, for example. Government agencies play a vital role in defining best practices for data anonymization and setting standards for how aggregated data may be used by both public entities and private companies [136].

5. IMPACT ON URBAN DEVELOPMENT AND SOCIETY

In this section, we explore the significant impact of the vehicles of the future on urban planning and the broad societal implications of this emerging technology. We begin by assessing the infrastructure transition timeline, identifying immediate changes needed for current infrastructure and the rate of transformation required to keep pace with vehicular deployment. This includes evaluating the effects on managing assets and planning for the lifecycle of both existing and new infrastructure compatible with CAVs. We then consider how these vehicles might alter urban land use and design. This covers potential changes in parking requirements, the redesign of the streets to support mixed-use areas and pedestrian safety, and new concepts for curbside management to accommodate flexible pick-up and drop-off points.

Additionally, we address important social and economic issues. This involves examining the potential for job displacement and the creation of new employment opportunities related to CAVs, ensuring fair access to this technology, and tackling privacy and cybersecurity concerns related to the generated data. Lastly, we focus on the essential topic of equitable access to CAV benefits. We analyze possible disparities in accessibility and affordability, as well as strategies to ensure that advantages are shared fairly, contributing to a more inclusive transportation system.

5.1 Timeline for Infrastructure Transformation

The integration of CAVs requires a methodical and phased strategy for infrastructure adaptation. Existing transportation networks, originally designed for human-driven vehicles, must be updated to support novel functionalities and demands. This transition must be carefully timed with the rollout of automated vehicles to ensure that the infrastructure evolves in step with these advancements.

One of the first steps is to adapt existing road markings, signage, and traffic signals to be understandable to both human drivers and vehicular sensors. The U.S. Department of Transportation (USDOT) [137] emphasizes the importance of uniform communication standards and infrastructure improvements to enable smooth interactions between vehicles and traffic control systems. For instance, lane markings might need to be more precise and reflective to be accurately detected by sensors, and traffic signals may need to communicate wirelessly to enable vehicles to anticipate changes and adjust their speed accordingly. Furthermore, the lifespan of the current infrastructure must be considered. Decisions about upgrades or replacements should reflect the expected rate of adoption and the likelihood of certain elements becoming outdated as technology progresses. This necessitates a shift in asset management practices, from traditional lifecycle planning to a more dynamic model that accounts for a mix of conventional and automated vehicles [138].

Additionally, the funding for infrastructural changes requires careful consideration. As previously discussed, PPPs could be instrumental in financing these, combining expertise and resources from both sectors for efficient and timely implementation. Companies developing CAV technologies might provide funding and know-how in exchange for access to public infrastructure and data, leading to a mutually beneficial collaboration. As technologies mature and their use becomes more widespread, the pace of infrastructure transformation will likely accelerate, requiring a flexible and responsive approach to urban planning and infrastructure management. Cities and transportation authorities must develop adaptable long-term plans that can be modified based on technological progress and shifts in travel patterns, ensuring that infrastructure is prepared for the future of transportation.

5.2 Effects on Urban Land Utilization and Design

The advent of CAVs has the potential to reshape urban land use and design, creating more livable, sustainable, and equitable cities. As the prevalence of automated vehicles increases and shared mobility services become more popular, the necessity for private car ownership might diminish. This could result in a substantial decrease in the need for parking spaces, allowing cities to repurpose urban areas currently used for parking lots and garages, turning them into parks, green spaces, or mixed-use developments, thereby improving the living conditions for city dwellers. Studies indicate that the broad acceptance of CAVs could reduce parking demand by up to 90% [139-141], liberating valuable urban land for more beneficial uses. This transition could promote greater density and walkability in urban centers, leading to livelier neighborhoods where residents can conveniently access amenities and services.

The design of streetscapes is also likely to be transformed as CAVs become integrated into the transportation system. With improved safety and predictability of automated vehicles, streets can finally be redesigned to prioritize pedestrians, cyclists, and public transportation. Wider sidewalks, dedicated bike lanes, and expanded public transit options can create a more balanced and equitable transportation network that promotes active modes of travel and reduces dependence on private vehicles. This shift towards more human-centric street design aligns with the principles of New Urbanism and Smart Growth, which emphasize creating walkable and mixed-use neighborhoods that prioritize people over cars [142]. Additionally, the precise vehicular navigation capabilities mean lanes can be narrower and road space can be used more efficiently compared to current road design, increasing the capacity of urban streets and potentially reducing the need to widen roads.

The emergence of CAVs also presents an opportunity to reimagine curbside management. Flexible pick-up and drop-off zones can be designated for ride-sharing services and automated delivery vehicles, reducing congestion and improving traffic flow [143]. Intelligent curb management systems can dynamically allocate curb space based on real-time demand, ensuring efficient use of this valuable urban resource, and potentially generate revenue for cities through dynamic pricing schemes [144, 145]. Additionally, dedicated lanes or designated areas for automated vehicles can be implemented to further optimize traffic flow and minimize disruption to other road users. This could involve creating separate lanes for CAVs on highways or designating specific zones within urban centers for automated delivery and ride-hailing services.

However, the transformation of urban land use and design due to these vehicles is not without its challenges. For instance, the reservation of parking spaces should prioritize the needs of residents who rely on on-street parking and ensure that affordable parking options remain available. Additionally, the design of pedestrian-friendly streetscapes should consider the needs of people with disabilities and ensure accessibility for all.

5.3 Socio-Economic Ramifications

A key issue of the introduction of CAVs is the potential loss of jobs, especially for drivers in the transport and logistics sectors. With more automated trucks and delivery vehicles, many driving jobs could be at risk. The International Transport Forum (ITF) [146] has estimated that up to 6.4 million driving jobs in the United States and Europe could be affected by automation. On the other hand, the vehicles of the future could also lead to new job opportunities in software development, vehicle engineering, and maintenance. There could also be new roles in managing vehicle fleets, operating vehicles remotely, and providing customer support for mobility services.

It is important to recognize that the transition towards CAVs is not without historical precedent. Throughout human history, technological transformations and paradigm shifts have consistently led to significant changes in workforce utilization. As societies transitioned from agrarian to industrial and subsequently to information-based economies, certain job categories became obsolete while new opportunities emerged. The shift towards connected vehicles represents a similar turning point and will require adaptation and retraining of the workforce to ensure a smooth transition.

While the potential displacement of drivers is a valid concern, it is essential to acknowledge that many transportation jobs are physically demanding, often involving long hours and inherent safety risks. Automated vehicles could alleviate these burdens and create opportunities for more fulfilling and less hazardous work. For example, companies such as Waymo and Cruise (from Google and General Motors, respectively), demand a big technological workforce, hiring hundreds of software engineers [147, 148], mainly focused on Machine Learning and simulation.

At the same time, cargo companies are facing problems in finding truck drivers, while the European Union, Norway, and the United Kingdom combined are currently short of over 233,000 truck drivers, with this number expected to increase up to 745,000 by 2028 [149].

With automated vehicles, logistics companies can have a fleet operating almost non-stop, providing safe rides without exhausted (and often exploited) drivers. In a possible transition, drivers would be able to take care of multiple trucks in a remote office, working more traditional hours and being closer to home.

It is also critical to ensure that the benefits of vehicular technology are available to everyone. There is a concern that the improvements these vehicles bring, such as better mobility and lower travel costs, might not reach all communities equally, which could worsen social inequalities. Strategies are needed to make sure that people with lower incomes, disabilities, or those living in rural areas can also use and afford CAVs. This might involve PPPs, offering financial assistance to those in need, and investing in transport infrastructure in areas that lack services.

5.4 Fairness and Accessibility of CAV Advantages

It is crucial to ensure that CAVs are affordable for people from all economic backgrounds. The high cost of new technology could worsen transportation inequalities, limiting access for those with lower incomes and marginalized groups [150, 151]. To prevent this, there are some alternatives, such as shared ownership, subsidized transport services, and integration of CAVs with public transport [152, 153]. These steps would help spread their benefits more widely, promoting social equity.

Digital literacy and access to technology are also essential for using these new vehicles effectively. The digital divide could leave some communities behind and unable to take advantage of their services and information [154]. Closing this gap requires investment in digital infrastructure and education to improve digital skills, ensuring everyone has the means to engage with CAV technology.

CAV design and rollout should also consider the needs of all potential users. Universal design principles applied to transportation could ensure that vehicles and their infrastructure are usable by everyone, including those with disabilities, older adults, and people with limited mobility [155]. This includes designing user-friendly interfaces and providing physical accommodation for passengers with disabilities. Furthermore, the deployment of CAVs should not be limited to wealthy areas or city centers, as this could increase spatial inequalities. Jiao & Dillivan [156] stress the importance of distributing transport infrastructure and services evenly to avoid creating areas without adequate transportation, known as transit deserts.

Finally, involving the public and affected communities in the planning and decision-making processes is essential for equitable adoption. Engaging a diverse range of stakeholders, especially citizen participation, will help identify equity concerns and develop community-centered solutions [157]. This collaborative approach will ensure that the transition to CAVs considers the needs and perspectives of all members of society, promoting a more just and equitable transportation future.

6. INTERCONNECTEDNESS OF CHALLENGES IN CAV DEPLOYMENT

The promise of connected and autonomous vehicles (CAVs) not only hinges on isolated technological breakthroughs but also on harmonizing a confusing situation for physical, digital, and policy systems. Urban transit and CAVs do not play well with isolated fixed systems, whereas the early adapters learned that the hard way. When we take into account Phoenix's 2023 robotaxi trial, monsoon rains washed out lanes' markings faster than the vehicles' high-definition maps could keep up and leave them stuck because they couldn't "see" the road [158].

While they individually examined these challenges. It is a clear lesson that CAVs need infrastructure, tech, and policy to evolve together, with policy holding it all together. This section tends to explain the examples drawn in section 2.5, emphasizing the need for a holistic approach to CAV deployment, considering these interdependencies.

6.1 Interconnection between Physical and Digital Infrastructure

The successful integration of CAVs demands a combined evolution of physical and digital infrastructure. Roadway adaptations, such as modified lane markings, signage, and dedicated CAV lanes (Section 2.1), are intrinsically linked to the capabilities of HD maps (Section 3.2) and V2I communication systems (Section 3.1).

At first glance, repainting lane markings seems a mundane task for municipal crews. Yet in the CAV era, these yellow lines become both physical guides and digital waypoints. Consider San Francisco's Presidio Parkway retrofit of narrower lanes (2.8m vs. standard 3.6m) were feasible only because CAVs' lateral control systems, calibrated to centimeter-precise HD maps, could navigate tighter spaces [159]. But when winter fog obscured LiDAR signals, vehicles defaulted to camera-based systems—which struggled with faded lane boundaries last repainted in 2019 [160] . The solution? A $4.2M investment in retroreflective paint with embedded RFID tags, detectable even in low visibility. This case epitomizes the symbiosis between infrastructure durability and digital resilience [161].

The placement of roadside units (RSUs) further illustrates this interdependence. Atlanta's Smart Corridor project initially clustered RSUs at major intersections, assuming 5G's 500m range would suffice [162]. Reality proved messier: signal attenuation from century-old oak canopies degraded V2I latency by 47%, forcing reinstallation on taller poles—a move that conflicted with historic preservation guidelines. Such clashes reveal how "smart" infrastructure must negotiate not just technical specs but community values and ecological constraints.

6.2 Policy as the Invisible Infrastructure

Regulatory frameworks often lag behind technological leaps, but their shaping power is profound. The EU's 2024 Cyber Resilience Act, mandating ISO/SAE 21434 compliance for all CAV components, has inadvertently reshaped urban design. To meet updated encryption standards, Boston's traffic signals now incorporate quantum-resistant chips—a $12M retrofit that delayed the city's CAV pilot by 18 months. Conversely, liability reforms can spur innovation: Japan's 2023 revision of the Road Transport Act, which caps manufacturer liability at 70% for L4 vehicle crashes, catalyzed Toyota's $2B investment in fail-operational braking systems.

Public-private partnerships (PPPs) amplify these dynamics. Los Angeles' Mobility Data Marketplace, a PPP initiative, exemplifies both promise and peril. By requiring automakers to share anonymized traffic data in exchange for access to dedicated CAV lanes, the city optimized signal timing—reducing congestion by 22%. However, privacy advocates noted that trip patterns from luxury AVs (predominantly servicing affluent areas) skewed infrastructure investments toward business districts, exacerbating transit inequities. This tension between efficiency and equity underscores policy's dual role as catalyst and constraint.

6.3 Data Management of CAV Ecosystem

At the heart of CAV deployment lies a paradox: the very data that enables smarter mobility also threatens to overwhelm existing systems. A single CAV can generate up to 4 terabytes of data per day, which is equivalent to streaming HD video for 1,200 hours. Managing this deluge requires rethinking traditional infrastructure. Edge computing has emerged as a critical solution, allowing vehicles to process safety-critical data locally (e.g., collision avoidance) while offloading non-urgent tasks to cloud systems [163]. Phoenix's 2023 pilot demonstrated this balance: by processing LiDAR data at roadside units (RSUs), emergency braking latency decreased by 37% compared to cloud-dependent systems [164].

Similarly, liability frameworks (Section 4.4) can incentivize investment in safety-focused infrastructure (Section 2.2) by assigning responsibility for accidents resulting from infrastructure deficiencies. Clear liability rules are therefore essential, properly allocating responsibility among vehicle manufacturers, software developers, infrastructure operators, and HD map providers. Initiatives like SAE J3216 aim to standardize vehicle-to-infrastructure (V2I) messaging, but adoption remains fragmented [165]. This standardization gap directly impacts urban planning-without unified data streams; cities struggle to justify infrastructure investments like dynamic lane markings or adaptive curbside zones discussed in Section 2.1.

Privacy concerns further complicate data utilization. The European Union's 2024 Data Act mandates CAV data anonymization, but researchers demonstrated how trip patterns from Berlin's robotaxis could still identify individuals through coffee shop visit correlations [166]. Differential privacy techniques, where "noise" is added to datasets, offer partial solutions but reduce HD map accuracy by up to 15% [167]. These trade-offs underscore why Rotterdam's mobility department now requires public review boards to approve all CAV data-sharing agreements [168].

6.4 Equity, Infrastructure and Societal Implications in CAV

The societal implications of CAVs – including urban land use changes, socio-economic impacts, and equity/accessibility – are inextricably linked to infrastructure and policy decisions, creating a dynamic feedback loop shaping urban environments. A potential reduced parking demand requires urban planning policies and infrastructure investments that repurpose parking spaces into green spaces or mixed-use developments, demanding collaboration among city planners, transportation agencies, and developers. Addressing job displacement necessitates proactive workforce retraining policies and the creation of new employment opportunities in areas such as CAV maintenance and data analysis, potentially involving partnerships between government, education, and industry.

Equitable access to CAV benefits requires careful consideration of infrastructure deployment, pricing models, and digital literacy needs across all communities. Deploying CAV infrastructure solely in wealthy areas would exacerbate existing inequalities; similarly, congestion pricing must consider the needs of low-income commuters. Therefore, detailed equity impact assessments and community engagement are necessary to ensure that CAV deployment benefits all members of society.

6.5 Cybersecurity in Connectivity

Cybersecurity is fundamental to the safety, reliability, and public acceptance of CAV technology. The interconnected nature of CAV systems – V2X communication, HD maps, and onboard sensors – creates a significant vulnerability to cyberattacks. Compromised HD maps could mislead CAVs, while compromised V2I systems could cause traffic disruptions or accidents. Therefore, robust cybersecurity is important for both safe operation and maintaining public trust. Security must be integrated into all infrastructure components, from physical roadways (e.g., RSU security) to digital networks (e.g., robust encryption). Strict security standards and protocols, directed through policy frameworks ,are necessary for vehicle manufacturers, infrastructure operators, and software developers, potentially including regular security audits, penetration testing, and intrusion detection systems.

6.6 Feedback Mechanisms and Contingency Planning

The interconnected challenges inherent in CAV integration are dynamic, involving feedback loops and potentially unforeseen consequences. Current decisions regarding infrastructure, policy, and technology will influence the long-term evolution of CAVs and their societal impact. For instance, data privacy policies (Section 4.5) will affect the development of data-driven traffic management (Section 3.3); strict regulations, while protecting individual rights, may limit data collection for optimizing traffic flow, whereas permissive regulations could erode public trust. Similarly, early infrastructure choices, such as the communication technology deployed (DSRC vs. 5G), may either facilitate or delay future advancements, with significant financial implications if a chosen technology becomes obsolete.

Therefore, it is key to have a flexible, adaptive approach to infrastructure planning and policy, adopting continuous learning and improvement. This requires ongoing monitoring of technological advancements, societal impacts, and public perception to proactively address emerging challenges, necessitating regular reviews of policies, infrastructure, and data management practices. Fostering collaboration and information sharing among stakeholders is fundamental to dealing with the complexities of CAV deployment and maximizing its benefits.

7. SUMMARY AND CONCLUSIONS

This paper has explored the comprehensive infrastructure requirements necessary for a successful transition towards widespread adoption of a Connected and Automated Vehicle (CAV). We examined the practical changes needed for both physical and digital infrastructure, including roadway adaptations, communication networks, data management systems, and cybersecurity measures. We also analyzed the broader societal implications of these vehicles, considering their impact on urban planning, social dynamics, and the need for equitable access to the benefits of this transformative technology. Additionally, we emphasized the crucial role of the public sector in facilitating this transition through strategic planning, partnerships with private companies, and regulations that cover safety standards, liability rules, data privacy, and ethical considerations.

A successful transition to CAVs will need a holistic approach that encompasses not only technological advancements but also robust policy frameworks that address safety, liability, data privacy, and ethical considerations. The main novelty of this work is that we propose an integrated discussion, highlighting the need for interdisciplinary collaboration and comprehensive policy frameworks to ensure a smooth and equitable transition to a future where these vehicles play a central role in transportation systems. These findings have important implications for policymakers, infrastructure planners, and transportation agencies seeking to facilitate this transition.

The potential impact of CAVs is far beyond transportation. They promise to reshape our cities, change how we get around, and transform how we live, work, and interact. Cities can become more pedestrian-friendly with less reliance on owning cars, which will give us the opportunity to turn parking lots into lively public spaces. Vehicular technology can also improve access for people with disabilities and underserved communities, while promoting more environmentally friendly transportation options.

However, to achieve this transformative vision, we need ongoing research and collaboration among the various stakeholders. The government plays a key role in managing the CAV transition by planning ahead, encouraging partnerships between public and private sectors, and creating flexible regulations. Further research is needed to understand the economic trade-offs of infrastructure investments, including developing models to analyze costs and benefits and determine the best time to invest based on CAV adoption rates. Additionally, more studies on social acceptance and community impact are crucial to understanding public perception, user acceptance of infrastructure changes, and the potential social and economic effects of CAVs on different communities.

Another important area for future research is to explore the development of dynamic and adaptable infrastructure that can adjust to evolving CAV capabilities and mixed traffic situations. This includes investigating smart signage, self-diagnosing systems, and other flexible technologies. Additionally, there is a need to establish ways of sharing data securely and consistently, along with strong cybersecurity measures to protect vehicular infrastructure and data privacy. Finally, research should focus on strategies for seamlessly integrating CAVs with existing public transportation systems and redesigning transportation hubs to optimize connections between different modes of travel.

Acknowledgement

The authors of this study want to cordially thank the Louisiana Department of Transportation, LA, USA, and the Roads and Highway Department, Bangladesh for supporting the study.

References

1. Sadaf M., Z. Iqbal, A. R. Javed, I. Saba, M. Krichen, S. Majeed, A. Raza. 2023. "Connected and Automated Vehicles: Infrastructure, Applications, Security, Critical Challenges, and Future Aspects". *Technologies (Basel)* 11(5): 117. ISSN: 2227-7080. DOI: https://doi.org/10.3390/technologies11050117.
2. Allied Market Research. 2025. "Autonomous Vehicle Market Size, Share, Competitive Landscape and Trend Analysis Report, by Level of Automation, by Component, by Vehicle Type : Global Opportunity Analysis and Industry Forecast, 2031-2040". Report.
3. Alsaid A., J. D. Lee, S. I. Noejovich, and A. Chehade. 2023. "The Effect of Vehicle Automation Styles on Drivers' Emotional State". *IEEE Transactions on Intelligent Transportation Systems* 24(4): 3963-3973. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2023.3239880

4. Nadia A. 2024. “Exploring the future: A meta-analysis of autonomous vehicle adoption and its impact on urban life and the healthcare sector”. *Transport Research Interdisciplinary Perspectives* 26: 101110. ISSN: 2590-1982. DOI: https://doi.org/10.1016/j.trip.2024.101110.
5. Parekh D., N. Poddar, A. Rajpurkar, M. Chahal, N. Kumar, G. P. Joshi, W. Cho. 2022. “A Review on Autonomous Vehicles: Progress, Methods and Challenges”. *Electronics* 11(14): 2162. ISSN: 2079-9292. DOI: https://doi.org/10.3390/electronics11142162.
6. Anderson J. M., N. Kalra, K. D. Stanley, P. Sorensen, C. Samaras, O. A. Oluwatola. 2016. Autonomous Vehicle Technology: A Guide for Policymakers. Santa Monica, CA: RAND Corporation.
7. Bajpai J. N. 2016 “Emerging vehicle technologies & the search for urban mobility solutions”. Urban Planning and Transport Research 4(1): 83-100. ISSN: 2165-0020. DOI: https://doi.org/10.1080/21650020.2016.1185964.
8. Milakis D., B. van Arem, and B. van Wee. 2017. “Policy and society related implications of automated driving: A review of literature and directions for future research,” *BIVEC-GIBET Transport Research Day, May 28-29, 2015, Eindhoven, The Netherlands*, The Netherlands, 2015. DOI: https://doi.org/10.1080/15472450.2017.1291351.
9. Ahangar M. N., Q. Z. Ahmed, F. A. Khan, and M. Hafeez. 2021. “A Survey of Autonomous Vehicles: Enabling Communication Technologies and Challenges”. *Sensors* 21(3): 706, DOI: https://doi.org/10.3390/s21030706.
10. Duarte F., C. Ratti. 2018. “The Impact of Autonomous Vehicles on Cities: A Review”. *Journal of Urban Technology* 25(4): 3-18. ISSN: 1063-0732. DOI: https://doi.org/10.1080/10630732.2018.1493883.
11. Gkartzonikas, C., K. Gkritza. 2019. “What have we learned? A review of stated preference and choice studies on autonomous vehicles”. *Transportation Research Part C: Emerging Technologies* 98: 323-337. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2018.12.003.
12. Hasenjager M., H. Wersing. 2017. “Personalization in advanced driver assistance systems and autonomous vehicles: A review”. In: *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC), IEEE*, 1-7. DOI: https://doi.org/10.1109/ITSC.2017.8317803.
13. Elbanhawi M., M. Simic, R. Jazar. 2015. “In the Passenger Seat: Investigating Ride Comfort Measures in Autonomous Cars”. *IEEE Intelligent Transportation Systems Magazine* 7(3): 84-96. ISSN: 1939-1374. DOI: https://doi.org/10.1109/mits.2015.2405571.
14. Huang Y., L. Qian. 2021. “Understanding the potential adoption of autonomous vehicles in China: The perspective of behavioral reasoning theory”. *Psychology & Marketing* 38(4): 669-690. ISSN: 0742-6046. DOI: https://doi.org/10.1002/mar.21465.
15. Jin . 2024. “Intelligent Vehicles and Smart Transportation”. *Fundamental Research* 4(5): 979-980. DOI: https://doi.org/10.1016/j.fmre.2024.08.004.
16. Gonzalez M., J. D. Idrobo, R. Taborda. 2019. “Family firms and financial performance: a meta-regression analysis”. *Academia Revista Latinoamericana de Administración* 32(3): 345-372. ISSN: 1012-8255. DOI: https://doi.org/10.1108/ARLA-09-2018-0213.
17. Liang Q., X. Li, Z. Chen, T. Pan, R. Zhong. 2023. “Day-to-day traffic control for networks mixed with regular human-piloted and connected autonomous vehicles”. *Transportation Research Part B: Methodological* 178: 102847. ISSN: 0191-2615. DOI: https://doi.org/10.1016/j.trb.2023.102847.

18. Liu Y., M. Tight, Q. Sun, R. Kang. 2019. "A systematic review: Road infrastructure requirement for Connected and Autonomous Vehicles (CAVs)". *Journal of Physics: Conference Series* 1187(4): 042073. ISSN: 1742-6596. DOI: https://doi.org/10.1088/1742-6596/1187/4/042073.
19. Hossain M. M., M. R. A. Lima, H. Zhou. 2024. "Potential Impacts of Connected and Autonomous Vehicles on Controlling Criteria for Road Geometric Design: A Review". *Transportation Research Record: Journal of the Transportation Research Board* 2678(11): 1128-1139. ISSN: 0361-1981. DOI: https://doi.org/10.1177/03611981241242764.
20. Shladover S. E., D. Su, X. Lu. 2012. "Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow". *Transportation Research Record: Journal of the Transportation Research Board* 2324(1): 63-70. ISSN: 0361-1981. DOI: https://doi.org/10.3141/2324-08.
21. Othman K. 2021. "Impact of Autonomous Vehicles on the Physical Infrastructure: Changes and Challenges". *Designs (Basel)* 5(3): 40. ISSN: 2411-4088. DOI: https://doi.org/10.3390/designs5030040.
22. Chen F., R. Balieu, N. Kringos. 2016. "Potential Influences on Long-Term Service Performance of Road Infrastructure by Automated Vehicles". *Transportation Research Record: Journal of the Transportation Research Board* 2550(1): 1-9. ISSN: 0361-1981. DOI: https://doi.org/10.3141/2550-10.
23. Mahmassani H. S. 2016. "50th Anniversary Invited Article – Autonomous Vehicles and Connected Vehicle Systems: Flow and Operations Considerations". *Transportation Science* 50(4): 1140-1162. ISSN: 0041-1655. DOI: https://doi.org/10.1287/trsc.2016.0712.
24. Khoury J., K. Amine, R. A. Saad, "An Initial Investigation of the Effects of a Fully Automated Vehicle Fleet on Geometric Design". *Journal of Advanced Transportation* 2019: 1-10. ISSN: 0197-6729. DOI: https://doi.org/10.1155/2019/6126408.
25. H. Liu, X. (David) Kan, S. E. Shladover, X. Lu, R. E. Ferlis. 2018. "Impact of cooperative adaptive cruise control on multilane freeway merge capacity". *Journal of Intelligent Transportation Systems* 22(3): 263-275. ISSN: 1547-1955. DOI: https://doi.org/10.1080/15472450.2018.1438275.
26. Monteiro F. V., P. Ioannou. 2023. "Safe autonomous lane changes and impact on traffic flow in a connected vehicle environment". *Transportation Research Part C: Emerging Technologies* 151: 104138. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2023.104138.
27. Fernandes P., U. Nunes. 2012. "Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow". *IEEE Transactions on Intelligent Transportation Systems* 13(1): 91-106. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2011.2179936.
28. Cav C., A. Colak, N. F. Unver. 2021. "Adaptive Traffic Signal Control to Reduce Delay Time at a Single Intersection Point". In: *2021 International Conference on Innovations in Intelligent SysTems and Applications (INISTA), IEEE*, 1-6. DOI: https://doi.org/10.1109/INISTA52262.2021.9548610.
29. Guo Q., L. Li, X. (Jeff) Ban. 2019. "Urban traffic signal control with connected and automated vehicles: A survey". *Transportation Research Part C: Emerging Technologies* 101: 313-334. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2019.01.026.

30. Dresner K., P. Stone. 2008. "A Multiagent Approach to Autonomous Intersection Management". *Journal of Artificial Intelligence Research* 31: 591-656. ISSN: 1076-9757. DOI: https://doi.org/10.1613/jair.2502.
31. Fiolić M., D. Babić, D. Babić, S. Tomasović. 2023. "Effect of road markings and road signs quality on driving behaviour, driver's gaze patterns and driver's cognitive load at night-time". *Transportation Research Part F: Traffic Psychology and Behaviour* 99: 306-318. ISSN: 1369-8478. DOI: https://doi.org/10.1016/j.trf.2023.10.025.
32. Mihalj T., H. Li, D. Babic, C. Lex, M. Jeudy, G. Zovak, D. Babic, A. Eichberger. 2022. "Road Infrastructure Challenges Faced by Automated Driving: A Review". *Applied Sciences* 12(7): 3477. ISSN: 2076-3417. DOI: https://doi.org/10.3390/app12073477.
33. Stantac and ARA. 2020 "Preparing for Automated Vehicles and Shared Mobility: State-of-the-Research Topical Paper #3 Infrastructure Enablers for Automated Vehicles and Shared Mobility". Washington, DC: Stantec/ARA.
34. Tengilimoglu O., O. Carsten, Z. Wadud. 2023. "Implications of automated vehicles for physical road environment: A comprehensive review". *Transportation Research Part E: Logistics and Transportation Review* 169: 102989. ISSN: 1366-5545. DOI: https://doi.org/10.1016/j.tre.2022.102989.
35. Ibrahim A. A., M. L. Abdullah. 2013. "The Effects of Vehicle Speed and Type of Road Surface on the Longitudinal Slip of Tires and the Brake Stopping Distance". *Engineering and Technology Journal* 31(10): 1854-1869. ISSN: 2078-9402. DOI: https://doi.org/10.30684/etj.31.10A4.
36. Cafiso S., A. Montella, C. D'Agostino, F. Mauriello, F. Galante. 2021. "Crash modification functions for pavement surface condition and geometric design indicators". *Accident Analysis & Prevention* 149: 105887. ISSN: 0001-4575. DOI: https://doi.org/10.1016/j.aap.2020.105887.
37. Ye Z., Y. Wei, W. Zhang, L. Wang. 2022. "An Efficient Real-Time Vehicle Monitoring Method". *IEEE Transactions on Intelligent Transportation Systems* 23(11): 22073-22083. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2022.3150224.
38. Li G., Y. Yang, X. Qu. 2020. "Deep Learning Approaches on Pedestrian Detection in Hazy Weather". *IEEE Transactions on Industrial Electronics* 67(10): 8889-8899. ISSN: 0278-0046. DOI: https://doi.org/10.1109/TIE.2019.2945295.
39. Tabatabai H. M. Aljuboori. 2017. "A Novel Concrete-Based Sensor for Detection of Ice and Water on Roads and Bridges". *Sensors* 17(12): 2912. ISSN: 1424-8220. DOI: https://doi.org/10.3390/s17122912.
40. Tamagusko T., A. Ferreira. 2023. "Machine Learning for Prediction of the International Roughness Index on Flexible Pavements: A Review, Challenges, and Future Directions". *Infrastructures (Basel)* 8(12): 170. ISSN: 2412-3811. DOI: https://doi.org/10.3390/infrastructures8120170.
41. Gulisano F., T. Buasiri, A. Cwirzen, J. Gallego. 2022. "Monitoring Road Infrastructures with Self-sensing Asphalt Pavements". In: *Lecture Notes in Civil Engineering*, 784–793. DOI: https://doi.org/10.1007/978-3-031-07254-3_79.
42. Tamagusko T., M. G. Correia, A. Ferreira. 2024. "Machine Learning Applications in Road Pavement Management: A Review, Challenges and Future Directions". *Infrastructures (Basel)* 9(12): 213. ISSN: 2412-3811. DOI: https://doi.org/10.3390/infrastructures9120213.
43. Somers A., D. Yee, S. Yee, A. Easswarakumar. 2023. "Minimum requirements for traffic signs, traffic signals and line markings". Report. Sydney, Australia.

44. Yuan J., Z. Jiao, X. Kong, J. Chai, K. Emura. 2025. “Application and development of retroreflective Materials: A review”. *Energy and Buildings* 337: 115707. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2025.115707.
45. Abbas A., M. Krichen, R. Alroobaea, S. Malebary, U. Tariq, M. J. Piran. 2021. “An opportunistic data dissemination for autonomous vehicles communication”. *Soft Computing* 25(18): 11899-11912. ISSN: 1432-7643. DOI: https://doi.org/10.1007/s00500-020-05542-y.
46. Reyes-Muñoz A. J. Guerrero-Ibáñez, “Vulnerable Road Users and Connected Autonomous Vehicles Interaction: A Survey”. *Sensors* 22(12): 4614. ISSN: 1424-8220. DOI: https://doi.org/10.3390/s22124614.
47. Kawanishi T., M. Shirai, T. Miura, K. Jitsuno, K. Inagaki, A. Kanno, N. Yamamoto. 2019. “Simple Secondary Radar for Non-Line-of-Sight Pedestrian Detection”. In: *IEEE International Conference on Antenna Measurements and Applications, Bali*, 1-5. DOI: https://doi.org/10.1109/CAMA47423.2019.8959735.
48. Nedevschi S., S. Bota, C. Tomiuc. 2009. “Stereo-Based Pedestrian Detection for Collision-Avoidance Applications”. *IEEE Transactions on Intelligent Transportation Systems* 10(3): 380-391. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2008.2012373.
49. Gavrila D. M., S. Munder. 2007. “Multi-cue Pedestrian Detection and Tracking from a Moving Vehicle”. *International Journal of Computer Vision* 73(1): 41–59. ISSN: 0920-5691. DOI: https://doi.org/10.1007/s11263-006-9038-7.
50. Gade R., T. B. Moeslund. 2014. “Thermal cameras and applications: a survey”. *Machine Vision Applications* 25(1): 245-262. ISSN: 0932-8092. DOI: https://doi.org/10.1007/s00138-013-0570-5.
51. Wang H., B. Wang, B. Liu, X. Meng, G. Yang. 2017. “Pedestrian recognition and tracking using 3D LiDAR for autonomous vehicle”. *Robotics and Autonomous Systems* 88: 71-78. ISSN: 0921-8890. DOI: https://doi.org/10.1016/j.robot.2016.11.014.
52. Zhao J., H. Xu, H. Liu, J. Wu, Y. Zheng, D. Wu. 2019. “Detection and tracking of pedestrians and vehicles using roadside LiDAR sensors”. *Transportation Research Part C: Emerging Technologies* 100: 68–87. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2019.01.007.
53. Xue S., E. Irannezhad, C. Karl. 2022. “Minimum physical infrastructure standard for the operation of automated driving part A: infrastructure investment”. Report. Sydney, Australia.
54. Yao Z., Y. Jiang, B. Zhao, X. Luo, B. Peng. 2019. “A dynamic optimization method for adaptive signal control in a connected vehicle environment”. *Journal of Intelligent Transportation Systems* 24(2): 184-200. ISSN: 1547-1955. DOI: https://doi.org/10.1080/15472450.2019.1643723.
55. Liu H., M. Yang, C. Guan, Y. S. Chen, M. Keith, M. You, M. Menendez. 2023. “Urban infrastructure design principles for connected and autonomous vehicles: a case study of Oxford, UK”. *Computational Urban Science* 3(1): 34. ISSN: 2676-0350. DOI: https://doi.org/10.1007/s43762-023-00110-0.
56. Mitteregger M., E. M. Bruck, A. Soteropoulos, A. Stickler, M. Berger, J. S. Dangschat, R. Scheuvens, I. Banerjee. 2021. “Connected and Automated Transport in the Long Level 4”. In: *Connected and Automated Vehicles: Prospects for Urban Europe.* 67-87. Springer Vieweg, Berlin, Heidelberg. DOI: https://doi.org/10.1007/978-3-662-64140-8_4.

57. Fagnant D. J., K. Kockelman. 2015. “Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations”. *Transportation Research Part A: Policy and Practice* 77: 167-181. ISSN: 0965-8564. DOI: https://doi.org/10.1016/j.tra.2015.04.003.
58. Millard-Ball A. 2019. “The autonomous vehicle parking problem”. *Transport Policy* 75: 99-108. ISSN: 0967-070X. DOI: https://doi.org/10.1016/j.tranpol.2019.01.003.
59. Sun Z., W. Gao, B. Li, L. Wang. 2018. “Locating charging stations for electric vehicles”. *Transport Policy* 98: 48-54. ISSN: 0967-070X. DOI: https://doi.org/10.1016/j.tranpol.2018.07.009.
60. Mo W., C. Yang, X. Chen, K. Lin, S. Duan. 2019. “Optimal Charging Navigation Strategy Design for Rapid Charging Electric Vehicles”. *Energies* 12(6): 962. ISSN: 1996-1073. DOI: https://doi.org/10.3390/en12060962.
61. Manzolli J. A., J. P. F. Trovão, C. H. Antunes. 2022. “Electric bus coordinated charging strategy considering V2G and battery degradation”. *Energy* 254: 124252. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2022.124252.
62. Melendez K. A., T. K. Das, C. Kwon. 2020. “Optimal operation of a system of charging hubs and a fleet of shared autonomous electric vehicles”. *Applied Energy* 279: 115861. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2020.115861.
63. Iacobucci R., B. McLellan, T. Tezuka. 2019. “Optimization of shared autonomous electric vehicles operations with charge scheduling and vehicle-to-grid”. *Transportation Research Part C: Emerging Technologies* 100: 34-52. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2019.01.011.
64. Kumru M., E. Debada, L. Makarem, D. Gillet. 2017. “Mobility-on-demand scenarios relying on lightweight autonomous and connected vehicles for large pedestrian areas and intermodal hubs”. In: *2017 2nd IEEE International Conference on Intelligent Transportation Engineering (ICITE), IEEE*, 178-183. DOI: https://doi.org/10.1109/ICITE.2017.8056904.
65. Alessandretti L., L. G. N. Orozco, M. Saberi, M. Szell, F. Battiston. 2023. “Multimodal urban mobility and multilayer transport networks”. *Environment and Planning B: Urban Analytics and City Science* 50(8): 2038-2070. ISSN: 2399-808X. DOI: https://doi.org/10.1177/23998083221108190.
66. Arnold T., M. Frost, A. Timmis, S. Dale, S. Ison. 2023. “Mobility Hubs: Review and Future Research Direction”. *Transportation Research Record: Journal of the Transportation Research Board* 2677(2): 858-868. ISSN: 0361-1981. DOI: https://doi.org/10.1177/03611981221108977.
67. Cai P., J. He, Y. Li. 2023. “Hybrid cooperative intersection management for connected automated vehicles and pedestrians”. *Journal of Intelligent and Connected Vehicles* 6(2): 91-101. DOI: https://doi.org/10.26599/JICV.2023.9210008.
68. Scott J., M. D’Arcangelo, B. Olness, M. Grimm, T. Bush. 2023. “An Assessment of Current Barriers to Accessibility in Public Transportation Pick Up/Drop Off Zones and How Solutions may be Applied to Autonomous Vehicles”. *SAE Technical Paper 2023-01-0713*. DOI: https://doi.org/10.4271/2023-01-0713.
69. Guanetti J., Y. Kim, F. Borrelli. 2018. “Control of connected and automated vehicles: State of the art and future challenges”. *Annual Review of Control* 45: 18-40. ISSN: 1367-5788. DOI: https://doi.org/10.1016/j.arcontrol.2018.04.011.
70. Kenney J. B. 2011. “Dedicated Short-Range Communications (DSRC) Standards in the United States”. *Proceedings of the IEEE* 99(7): 1162-1182. ISSN: 0018-9219. DOI: https://doi.org/10.1109/JPROC.2011.2132798.

71. Ma Y., M. Chowdhury, A. Sadek, M. Jeihani. 2012. “Integrated Traffic and Communication Performance Evaluation of an Intelligent Vehicle Infrastructure Integration (VII) System for Online Travel-Time Prediction”. *IEEE Transactions on Intelligent Transportation Systems* 13(3): 1369-1382. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2012.2198644.
72. Dey K. C., A. Rayamajhi, M. Chowdhury, P. Bhavsar, J. Martin. 2016. “Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication in a heterogeneous wireless network – Performance evaluation”. *Transportation Research Part C: Emerging Technologies* 68: 168-184. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2016.03.008.
73. Luu Q., T. M. Nguyen, N. Zheng, H. L. Vu, “Digital Infrastructure for Connected and Automated Vehicles”. *arXiv*. DOI: https://doi.org/10.48550/arXiv.2401.08613.
74. Nkenyereye L., L. Nkenyereye, Q. Pham, J. Song, “Efficient RSU Selection Scheme for Fog-Based Vehicular Software-Defined Network”. *IEEE Transactions on Vehicular Technology* 70(11): 12126-12141. ISSN: 0018-9545. DOI: https://doi.org/10.1109/TVT.2021.3116811.
75. Abboud K., H. A. Omar, W. Zhuang. 2016. “Interworking of DSRC and Cellular Network Technologies for V2X Communications: A Survey”. *IEEE Transactions on Vehicular Technology* 65(12): 9457-9470. ISSN: 0018-9545. DOI: https://doi.org/10.1109/TVT.2016.2591558.
76. Fang J., R. Xu, Y. Yang, X. Li, S. Zhang, X. Peng, X. Liu. 2017. “Introduction and simulation of dedicated short range communication”. In: *2017 IEEE 5th International Symposium on Electromagnetic Compatibility (EMC-Beijing), IEEE,* 1-10. DOI: https://doi.org/10.1109/EMC-B.2017.8260392.
77. Wang K., C. She, Z. Li, T. Yu, Y. Li, K. Sakaguchi. 2024. “Roadside Units Assisted Localized Automated Vehicle Maneuvering: An Offline Reinforcement Learning Approach”. Report. Sydney, Australia.
78. Dharmaraja S., R. Vinayak, K. S. Trivedi. 2016. “Reliability and survivability of vehicular ad hoc networks: An analytical approach”. *Reliability Engineering & System Safety* 153: 28-38. ISSN: 0951-8320. DOI: https://doi.org/10.1016/j.ress.2016.04.004.
79. Papathanassiou A., A. Khoryaev. 2017. “Cellular V2X as the Essential Enabler of Superior Global Connected Transportation Services”. *IEEE 5G Tech Focus* 1(2): 5–12.
80. Odida M. O. 2024. “The Evolution of Mobile Communication: A Comprehensive Survey on 5G Technology”. *Journal of Sensor Networks and Data Communications* 4(1): 01-11. ISSN: 2470-3871. DOI: https://doi.org/10.33140/JSNDC.04.01.06.
81. Ullah H., N. G. Nair, A. Moore, C. Nugent, P. Muschamp, and M. Cuevas. 2019. “5G Communication: An Overview of Vehicle-to-Everything, Drones, and Healthcare Use-Cases”. *IEEE Access* 7: 37251-37268. ISSN: 2169-3536. DOI: https://doi.org/10.1109/ACCESS.2019.2905347.
82. Molina-Masegosa R., J. Gozalvez, “LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications”. *IEEE Vehicular Technology Magazine* 12(4): 30-39. ISSN: 1556-6072. DOI: https://doi.org/10.1109/MVT.2017.2752798.
83. Liu S., B. Yu, J. Tang, Y. Zhu, X. Liu. 2022. “Communication Challenges in Infrastructure-Vehicle Cooperative Autonomous Driving: A Field Deployment Perspective”. *IEEE Wireless Communications* 29(4): 126-131. ISSN: 1536-1284. DOI: https://doi.org/10.1109/MWC.005.2100539.

84. Campbell S., N. O'Mahony, L. Krpalcova, D. Riordan, J. Walsh, A. Murphy, C. Ryan. 2018. "Sensor Technology in Autonomous Vehicles: A review". In: *2018 29th Irish Signals and Systems Conference (ISSC), IEEE,* 1-4. DOI: https://doi.org/10.1109/ISSC.2018.8585340.
85. Alaba S. Y. 2024. "GPS-IMU Sensor Fusion for Reliable Autonomous Vehicle Position Estimation". *arXiv*. DOI: https://doi.org/10.48550/arXiv.2405.08119.
86. Correia M. G., A. Ferreira. 2023. "Road Asset Management and the Vehicles of the Future: An Overview, Opportunities, and Challenges". *International Journal of Intelligent Transportation Systems Research* 21(3): 376-393. ISSN: 1936-6744. DOI: https://doi.org/10.1007/s13177-023-00366-0.
87. Guan H., J. Li, S. Cao, Y. Yu. 2016. "Use of mobile LiDAR in road information inventory: a review". *International Journal of Image and Data Fusion* 7(3): 219-242. ISSN: 1947-986X. DOI: https://doi.org/10.1080/19479832.2016.1188860.
88. Alim A., A. Joshi, F. Chen, C. T. Lawson. 2020. "Techniques for efficient detection of rapid weather changes and analysis of their impacts on a highway network". *Geoinformatica* 24(2): 269-299. ISSN: 1384-6175. DOI: https://doi.org/10.1007/s10707-020-00395-x.
89. Schwietering C., M. Feldges. 2016. "Improving Traffic Flow at Long-term Roadworks". *Transportation Research Procedia* 15: 267-282. ISSN: 2352-1465. DOI: https://doi.org/10.1016/j.trpro.2016.06.023.
90. Chin S. M., O. Franzese, D. L. Greene, H. L. Hwang. 2002. "Temporary Losses of Highway Capacity and Impacts on Performance". In Oak Ridge National Laboratory Technical Memorandum ORNL/TM-2002/3. Knoxville, Tennessee.
91. Sasaki K., N. Suzuki, S. Makido, A. Nakao. 2016. "Vehicle control system coordinated between cloud and mobile edge computing". In: *2016 55th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE), IEEE,* 1122-1127. DOI: https://doi.org/10.1109/SICE.2016.7749210.
92. Biswas A., H. Wang. 2023. "Autonomous Vehicles Enabled by the Integration of IoT, Edge Intelligence, 5G, and Blockchain". *Sensors* 23(4): 1963. ISSN: 1424-8220. DOI: https://doi.org/10.3390/s23041963.
93. Lu S., W. Shi. 2023. "Vehicle Computing: Vision and challenges". *Journal of Information and Intelligence* 1(1): 23-35. ISSN: 2769-7422. DOI: https://doi.org/10.1016/j.jiixd.2022.10.001.
94. Kara P. A., A. Wippelhauser, T. Balogh, L. Bokor. 2023. "How I Met Your V2X Sensor Data: Analysis of Projection-Based Light Field Visualization for Vehicle-to-Everything Communication Protocols and Use Cases". *Sensors* 23(3): 1284. ISSN: 1424-8220. DOI: https://doi.org/10.3390/s23031284.
95. Arthurs P., L. Gillam, P. Krause, N. Wang, K. Halder, A. Mouzakitis. 2022. "A Taxonomy and Survey of Edge Cloud Computing for Intelligent Transportation Systems and Connected Vehicles". *IEEE Transactions on Intelligent Transportation Systems* 23(7): 6206-6221. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2021.3084396.
96. Ansari M. R., J. Monteuuis, J. Petit, C. Chen. 2021. "V2X Misbehavior and Collective Perception Service: Considerations for Standardization". In: *2021 IEEE Conference on Standards for Communications and Networking (CSCN), IEEE,* 1-6. DOI: https://doi.org/10.1109/CSCN53733.2021.9686156.
97. SAE. 2024. V2X Communications Message Set Dictionary: J2735_202409. *SAE International*.

98. Giannaros A., A. Karras, L. Theodorakopoulos, C. Karras, P. Kranias, N. Schizas, G. Kalogeratos, D. Tsolis. 2023. “Autonomous Vehicles: Sophisticated Attacks, Safety Issues, Challenges, Open Topics, Blockchain, and Future Directions”. *Journal of Cybersecurity and Privacy* 3(3): 493-543. ISSN: 2624-800X. DOI: https://doi.org/10.3390/jcp3030025.
99. Nathanson M. D. 2013. “Automative Telemetry Protocol”. US Patent 8,560,609 B2
100. Taeihagh A., H. S. M. Lim. 2019 “Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks”. *Transport Reviews* 39(1): 103-128. ISSN: 0144-1647. DOI: https://doi.org/10.1080/01441647.2018.1494640.
101. Glancy D. J. 2012. “Privacy in Autonomous Vehicles,” *Santa Clara Law Review 52(4).*
102. Krontiris I., K. Grammenou, K. Terziduo, M. Zacharopoulou, M. Tsikintikou, F. Baladima, C. Sakellari, K. Kaouras. 2020. “Autonomous Vehicles: Data Protection and Ethical Considerations”. In: *Computer Science in Cars Symposium, New York, NY, USA: ACM,* 1-10. DOI: https://doi.org/10.1145/3385958.3430481.
103. Cunneen M., M. Mullins, F. Murphy, D. Shannon, I. Furxhi, C. Ryan. 2020. “Autonomous Vehicles and Avoiding the Trolley (Dilemma): Vehicle Perception, Classification, and the Challenges of Framing Decision Ethics”. *Cybernetics and Systems* 51(1): 59-80. ISSN: 0196-9722. DOI: https://doi.org/10.1080/01969722.2019.1660541.
104. Hamida E., H. Noura, W. Znaidi. 2015. “Security of Cooperative Intelligent Transport Systems: Standards, Threats Analysis and Cryptographic Countermeasures”. *Electronics* 4(3): 380-423. ISSN: 2079-9292. DOI: https://doi.org/10.3390/electronics4030380.
105. Sun X., F. R. Yu, P. Zhang. 2022. “A Survey on Cyber-Security of Connected and Autonomous Vehicles (CAVs)”. *IEEE Transactions on Intelligent Transportation Systems* 23(7): 6240-6259. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2021.3085297.
106. Parkinson S., P. Ward, K. Wilson, J. Miller. 2017. “Cyber Threats Facing Autonomous and Connected Vehicles: Future Challenges”. *IEEE Transactions on Intelligent Transportation Systems* 18(11): 2898-2915. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2017.2665968.
107. Eykholt K., I. Evtimov, E. Fernandes, B. Li, A. Rahmati, C. Xiao, T. Kohno, D. Song. 2017. “Robust Physical-World Attacks on Deep Learning Models”. *arXiv*. DOI: https://doi.org/10.48550/arXiv.1707.08945.
108. Wei X., Y. Guo, J. Yu. 2022. “Adversarial Sticker: A Stealthy Attack Method in the Physical World”. *IEEE Transactions on Pattern Analysis and Machine Intelligence*. DOI: https://doi.org/10.1109/TPAMI.2022.3176760.
109. Pavlitska S., N. Lambing, J. M. Zöllner. 2023. “Adversarial Attacks on Traffic Sign Recognition: A Survey”. In: *2023 3rd International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), IEEE,* 1-6. DOI: https://doi.org/10.1109/ICECCME57830.2023.10252727.
110. Muttoo S. K., V. Kumar. 2012. “Watermarking digital vector map using graph theoretic approach”. *Annals of GIS* 18(2): 135-146. ISSN: 1947-5682. DOI: https://doi.org/10.1080/19475683.2011.640640.

111. Juhász L., T. Novack, H. H. Hochmair, S. Qiao. 2020. "Cartographic Vandalism in the Era of Location-Based Games – The Case of OpenStreetMap and Pokémon GO". *ISPRS International Journal of Geo-Information* 9(4): 197. ISSN: 2220-9964. DOI: https://doi.org/10.3390/ijgi9040197.
112. Chen C., B. Xiang, Y. Liu, K. Wang. 2019. "A Secure Authentication Protocol for Internet of Vehicles". *IEEE Access* 7: 12047-12057. ISSN: 2169-3536. DOI: https://doi.org/10.1109/ACCESS.2019.2891105.
113. Ghosh S., A. Zaboli, J. Hong, J. Kwon. 2023. "An Integrated Approach of Threat Analysis for Autonomous Vehicles Perception System". *IEEE Access* 11: 14752-14777. ISSN: 2169-3536. DOI: https://doi.org/10.1109/ACCESS.2023.3243906.
114. VicOne. 2023. "Security Insights: EV Manufacturer NIO Discloses Data Breach". *VicOne*.
115. Staff. 2023. "Report: 'massive' Tesla leak reveals data breaches, thousands of safety complaints". *The Guardian*.
116. Elefteriadou L., B. Leonard, L. Du, W. Ma, J. Liu, K. Zhang, J. Ma, Z. Song, X. Li, S. Erdogan. 2020. "Enabling Transportation Networks with Automated Vehicles: From Individual Vehicle Motion Control to Networked Fleet Management". In: *Automated Driving, Cham: Springer International Publishing*, 49-62. DOI: https://doi.org/10.1007/978-3-030-52840-9_5.
117. Tengilimoglu O., O. Carsten, Z. Wadud. 2023. "Infrastructure requirements for the safe operation of automated vehicles: Opinions from experts and stakeholders". *Transport Policy* 133: 209-222. ISSN: 0967-070X. DOI: https://doi.org/10.1016/j.tranpol.2023.02.001.
118. Toth C., F. Perry, A. Keshmiri. 2025. "RES2023-29: Connected and Autonomous Vehicle Readiness Action Plan". Nashville, Tennessee.
119. Wen J., Y. X. Chen, N. Nassir, J. Zhao. 2018. "Transit-oriented autonomous vehicle operation with integrated demand-supply interaction". *Transportation Research Part C: Emerging Technologies* 97: 216-234. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2018.10.018.
120. Nowakowski C., S. E. Shladover, C. Chan, H. Tan. 2015. "Development of California Regulations to Govern Testing and Operation of Automated Driving Systems". *Transportation Research Record: Journal of the Transportation Research Board* 2489(1): 137-144. ISSN: 0361-1981. DOI: https://doi.org/10.3141/2489-16.
121. Lim H. S. M., A. Taeihagh. 2019. "Algorithmic Decision-Making in AVs: Understanding Ethical and Technical Concerns for Smart Cities". *Sustainability* 11(20): 5791. ISSN: 2071-1050. DOI: https://doi.org/10.3390/su11205791.
122. Takacs A., D. A. Drexler, P. Galambos, I. J. Rudas, T. Haidegger. 2018. "Assessment and Standardization of Autonomous Vehicles". In: *2018 IEEE 22nd International Conference on Intelligent Engineering Systems (INES), IEEE,* 000185-000192. DOI: https://doi.org/10.1109/INES.2018.8523899.
123. Acerete B., M. Gasca, A. Stafford. 2019. "Two Decades of DBFO Roads in the UK and Spain: An Evaluation of the Financial Performance". *Annals of Public and Cooperative Economics* 90(2): 269-289. ISSN: 1467-8292. DOI: https://doi.org/10.1111/apce.12237.
124. Fayard A. 2005. "Analysis of Highway Concession in Europe". *Research in Transportation Economics* 15: 15-28. ISSN: 0739-8859. DOI: https://doi.org/10.1016/S0739-8859(05)15002-1.

125. Qiu C. S. Yadav, A. Squicciarini, Q. Yang, S. Fu, J. Zhao. 2022. “Distributed Data-Sharing Consensus in Cooperative Perception of Autonomous Vehicles”. In: *2022 IEEE 42nd International Conference on Distributed Computing Systems (ICDCS), IEEE*, 1212-1222. DOI: https://doi.org/10.1109/ICDCS54860.2022.00119.
126. Los J., F. Schulte, M. T. J. Spaan, R. R. Negenborn. 2020. “The value of information sharing for platform-based collaborative vehicle routing”. *Transportation Research Part E: Logistics and Transportation Review* 141: 102011. ISSN: 1366-5545. DOI: https://doi.org/10.1016/j.tre.2020.102011.
127. Damsgaard J., K. Kyytinen. 2001. “The Role of Intermediating Institutions in the Diffusion of Electronic Data Interchange (EDI): How Industry Associations Intervened in Denmark, Finland, and Hong Kong”. *The Information Society* 17(3): 195-210. ISSN: 0197-2243. DOI: https://doi.org/10.1080/01972240120907.
128. UNECE. 2025. Vehicle Regulations. Geneva.
129. Bakirtzis G., S. Carr, D. Danks, U. Topcu. 2022. “Dynamic Certification for Autonomous Systems”. *Communications of the ACM* 66(9): 64-72. DOI: https://doi.org/10.1145/3574133.
130. Koopman P., M. Wagner. 2016. “Challenges in Autonomous Vehicle Testing and Validation”. *SAE International Journal of Transportation Safety* 4(1): 2016-01–0128. ISSN: 2577-3771. DOI: https://doi.org/10.4271/2016-01-0128.
131. Hansson L. 2020. “Regulatory governance in emerging technologies: The case of autonomous vehicles in Sweden and Norway”. *Research in Transportation Economics* 83: 100967. ISSN: 0739-8859. DOI: https://doi.org/10.1016/j.retrec.2020.100967.
132. Carp J. A. 2018. “Autonomous Vehicles: Problems and Principles for Future Regulation”. *Journal of Law & Public Affairs* 4(1). Available at: https://scholarship.law.upenn.edu/jlpa/vol4/iss1/5
133. Sheehan B., F. Murphy, C. Ryan, M. Mullins, H. Y. Liu. 2017. “Semi-autonomous vehicle motor insurance: A Bayesian Network risk transfer approach”. *Transportation Research Part C: Emerging Technologies* 82: 124-137. ISSN: 0968-090X. DOI: https://doi.org/10.1016/j.trc.2017.06.015.
134. Determann L. 2019. “No One Owns Data”. Hastings Law Journal 70(1). Available at: https://repository.uclawsf.edu/hastings_law_journal/vol70/iss1/1.
135. Pype P., G. Daalderop, E. Schulz-Kamm, E. Walters, and M. von Grafenstein. 2017. “Privacy and Security in Autonomous Vehicles”. In: *Automated Driving, Cham: Springer International Publishing*, 17-27. DOI: https://doi.org/10.1007/978-3-319-31895-0_2.
136. Ajina M., B. Yousefi, J. Jones, K. Laskey. 2019. “Secure Method for De-Identifying and Anonymizing Large Panel Datasets”. In: *2019 22nd International Conference on Information Fusion (FUSION), IEEE*, 1-7. DOI: https://doi.org/10.23919/FUSION43075.2019.9011394.
137. USDOT. 2018. Preparing for the Future of Transportation: Automated Vehicles 3.0. Washington, D.C. Available at: https://www.transportation.gov/av/3.
138. Osichenko D. R. Spielhofer. 2018. “Future challenges for the Road Asset Management”. *Transportation Engineering Procedia* 36: 979-985. DOI: https://doi.org/10.5592/CO/CETRA.2018.708.
139. Silva D., D. Földes, C. Csiszár. 2021. “Autonomous Vehicle Use and Urban Space Transformation: A Scenario Building and Analysing Method”. *Sustainability* 13(6): 3008. ISSN: 2071-1050. DOI: https://doi.org/10.3390/su13063008.

140. Nourinejad M., S. Bahrami, M. J. Roorda. 2017. "Designing parking facilities for autonomous vehicles". *Transportation Research Part B: Methodological* 109: 110-127. ISSN: 0191-2615. DOI: https://doi.org/10.1016/j.trb.2017.12.017.
141. Zhang W., S. Guhathakurta, J. Fang, G. Zhang. 2015. "Exploring the impact of shared autonomous vehicles on urban parking demand: An agent-based simulation approach," *Sustainable Cities and Society*: 19: 34-45. DOI: https://doi.org/10.1016/j.scs.2015.07.006.
142. Katz P. 1994. The New Urbanism: Toward an Architecture of Community. New York, USA: McGraw-Hill.
143. Hunter C. B., K. M. Kockelman, S. Djavadian. 2024. "Curb Allocation and Pick-Up Drop-Off Aggregation for a Shared Autonomous Vehicle Fleet". *International Regional Science Review* 47(2): 131-158. ISSN: 0160-0153. DOI: https://doi.org/10.1177/01600176231160498.
144. Diehl C., A. Ranjbari, A. Goodchild. 2021. "Curbspace Management Challenges and Opportunities from Public and Private Sector Perspectives". *Transportation Research Record: Journal of the Transportation Research Board* 2675(11): 1413-1427. ISSN: 0361-1981. DOI: https://doi.org/10.1177/03611981211027156.
145. Ye Q., Y. Feng, J. Qiu, M. Stettler, P. Angeloudis. 2022. "Approximate Optimum Curbside Utilisation for Pick-Up and Drop-Off (PUDO) and Parking Demands Using Reinforcement Learning". In: *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC), IEEE,* 2628-2633. DOI: https://doi.org/10.1109/ITSC55140.2022.9922036.
146. ITF. 2017. Managing the Transition to Driverless Road Freight Transport. Paris, France.
147. Cruise. 2025. Open Positions. Online.
148. Waymo. 2025. Careers in Tech. Online.
149. IRU. 2024. Global Truck Driver Shortage Report 2024 – Europe. Geneva, Switzerland.
150. Litman T. 2024. *Autonomous Vehicle Implementation Predictions Implications for Transport Planning*. Victoria, Canada.
151. Parkes S., E. Ferrari. 2022. *Connected and Autonomous Vehicles*. London: Routledge. ISBN: 978-1-032-89883-2. DOI: https://doi.org/10.4324/9781003348832.
152. Whitmore A., C. Samaras, C. T. Hendrickson, H. S. Matthews, G. Wong-Parodi. 2022. "Integrating public transportation and shared autonomous mobility for equitable transit coverage: A cost-efficiency analysis". *Transport Research Interdisciplinary Perspectives* 14: 100571. ISSN: 2590-1982. DOI: https://doi.org/10.1016/j.trip.2022.100571.
153. Imhof S., J. Frölicher, W. von Arx. 2020. "Shared Autonomous Vehicles in rural public transportation systems". *Research in Transportation Economics* 83: 100925. ISSN: 0739-8859. DOI: https://doi.org/10.1016/j.retrec.2020.100925.
154. Khan S. M., M. S. Salek, V. Harris, G. Comert, E. A. Morris, M. Chowdhury. 2024. "Autonomous Vehicles for All?". *ACM Journal on Autonomous Transportation Systems* 1(1): 1-8. ISSN: 2768-2754. DOI: https://doi.org/10.1145/3611017.
155. Steinfeld E. J. Maisel. 2012. *Universal Design: Creating Inclusive Environments*. New York, USA: Wiley. ISBN: 978-0-470-39913-2.
156. Jiao J., M. Dillivan. 2013. "Transit Deserts: The Gap between Demand and Supply". *Journal of Public Transportation* 16(3): 23-39. ISSN: 2375-0901. DOI: https://doi.org/10.5038/2375-0901.16.3.2.

157. Arnstein S. R. 1969. "A Ladder of Citizen Participation". *Journal of the American Institute of Planners* 35(4): 216-224. ISSN: 0194-4363. DOI: https://doi.org/10.1080/01944366908977225.
158. Bloomberg. 2018. "Phoenix Robotaxi: Self-Driving Cars Can Handle Neither Rain nor Sleet nor Snow". Bloomberg. Available at: http://www.bloomberg.com.
159. SFMTA. 2023. Muni Maintenance, Rehabilitation, and Replacement. San Francisco.
160. Yang T., Y. Li, Y. Ruichek, Z. Yan. 2022. "Performance Modeling a Near-Infrared ToF LiDAR Under Fog: A Data-Driven Approach". *IEEE Transactions on Intelligent Transportation Systems* 23(8): 11227-11236. ISSN: 1524-9050. DOI: https://doi.org/10.1109/TITS.2021.3102138.
161. Brinded A. 2024. "In the dark – reflective paint helps autonomous vehicles see more clearly". Institute of Materials, Minerals & Mining, Austin, Texas.
162. Nlenanya I., A. Inusah, S. Hallmark. 2022. "Aurora Project 2022-08: Integration of Connected Vehicle and RWIS Technologies". Report. Lincoln Way, Ames.
163. Bharati M. 2025. "Navigating the Future: Mobile Edge Computing Revolutionizing Data in Autonomous Vehicles". *360iResearch*.
164. Khan W. Z., M. K. Khan, Q. Arshad. 2023. "Cybersecurity Digital Labels for Connected and Autonomous Vehicles". *IEEE Consumer Electronics Magazine* 12(1): 87-93. ISSN: 2374-8999. DOI: https://doi.org/10.1109/MCE.2021.3119857.
165. Tanaji B. A., S. Roychowdhury. 2025. "A Survey of Cybersecurity Challenges and Mitigation Techniques for Connected and Autonomous Vehicles". *IEEE Transactions on Intelligent Vehicles*. DOI: https://doi.org/10.1109/TIV.2024.3493938.
166. Znidi F., M. Morsy, H. Rathore. 2024. "Future on Wheels: Safeguarding Privacy in Tomorrow's Connected Vehicles-FUTURE-SP". *IEEE Access* 12: 179857-179878. ISSN: 2169-3536. DOI: https://doi.org/10.1109/ACCESS.2024.3505158.
167. Moussa M. M., L. Alazzawi, "IoT-Based Dynamic Map Attributes for Connected and Autonomous Vehicles". In: *2021 IEEE International Smart Cities Conference (ISC2), IEEE*, 1-6. DOI: https://doi.org/10.1109/ISC253183.2021.9562957.
168. Stantec and ARA. 2020. "NCHRP Project 20-113F: Prioritizing Equity, Accessibility and Inclusion around the Deployment of Automated Vehicles". Washington, DC.

Received 28.05.2025; accepted in revised form 11.08.2025