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Review

The Emergence of Automated Vehicles and their Potential Implications for Urban Mobility: A Review of the Literature and Synthesis of Use Cases

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Abstract: Automated vehicles (AVs), which are expected to enter the market within the near future, represent the current frontiers in mobility and urban planning. AVs are assumed to bring substantial benefits to cities in many aspects. The present study attempts to investigate this broad assumption by conducting a literature review on the possible implications of AVs in cities as well as synthesizing the current state of practice of AV pilots to detect trends in their deployment. In this paper, literature findings on AVs' implication on vehicle ownership, mobility, land use as well thirteen uses cases were synthesized to capture the big picture of them in cities. The findings showed that, in the AV pilots, the operation of AVs is limited to routes stretching less than 3.5km and an operation speed of less than 18km/h; low speed has been one of the main concerns of the participating passengers to use them for daily trips. The results also revealed that although shared AVs are expected in urban mobility, private ownership will stay competitive since vehicle ownership has been a socio-cultural identity in the history of automobiles. The findings also underlined that the potential influence of AVs on active mobility is still unclear as the AVs have not been introduced on a larger scale. Regarding AVs' impact on land use, their introduction results in the effective use of space, but they will cause suburbanization in the long term.

Keywords: automated vehicles; land use; potential implication; urban mobility; use cases

1. Introduction

Automated vehicles (AVs) are today's automotive and urban planning frontiers that bring two paradoxes of impact: benefit and hazard. The urban mobility landscape has been changing over time with inventions and technological advancements. Centuries ago, large cities (e.g., New York) relied overwhelmingly on horse-powered, considered as one of the newest technologies at the time despite the negative impacts on urban livability [1]. Later, automobiles powered by engines replaced horses. Considered as a revolution improving urban mobility, it has brought negative externalities to modern cities (e.g., emissions and congestion). Thus, stakeholders have been looking for transportation alternatives among which AV is an attractive candidate [2]. AVs' potential impacts could be like the first internal combustion engine vehicles introduced to the urban environment centuries ago, replacing horse-drawn transportation.

Testing and regulating AVs might take a few years, as estimated by the vehicle industry. However, deterring issues rise, including the unpredictable interaction of AVs with conventional vehicles, VRUs, and animals [3]. Nevertheless, Zhang et al. [4] showed, for example, that the market penetration of level 4 AVs in US cities could reach 34% (70% private and 30% shared) in 2030 and 75% (50% private and 50% shared) in 2040. The 2020s decade is the development and testing timeline of AVs, with the expectation that this

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technology will be available on the market in the 2030s at high price. By the 2030s, AVs are expected to hit the urban roads with significant penetration in the form of shared mobility [5]. The affordability of AVs will increase starting from 2040, and it is believed that 50% of new vehicle sales will be AVs by 2045 [6], which also demonstrates that the adoption of AVs will follow Roger's S-shaped curve with several stages including concept, development, testing, commercial release, product improvement, expansion, market diffusion, maturation, saturation, and finally decline as displayed in Figure 1 [6]. Nonetheless, to the best of the authors' knowledge, there is nothing certain about having private AVs (level 4 minimum) hitting the urban roads, and AVs will most likely be shared for public use.

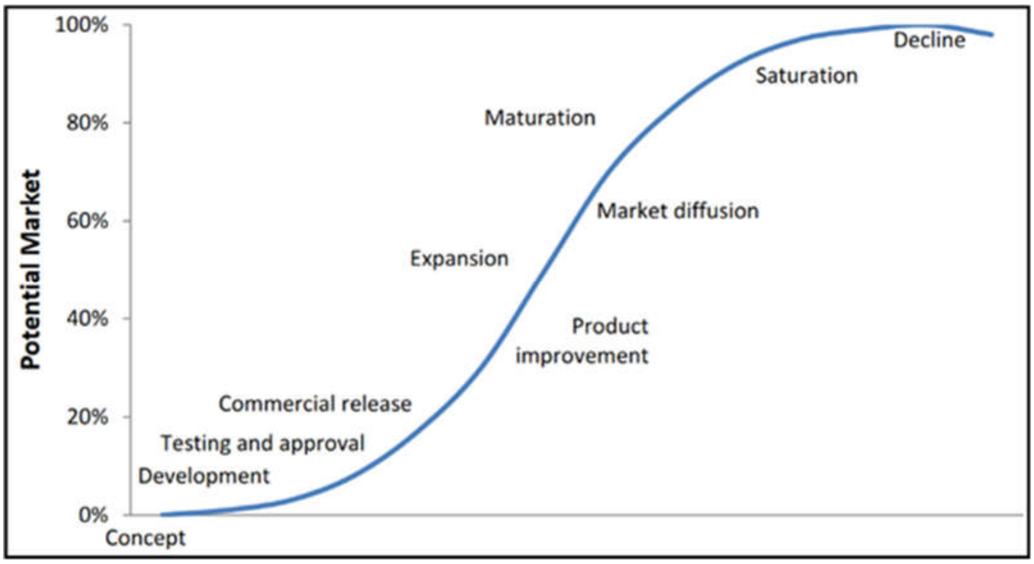

Figure 1. Prediction of the pattern of AVs market

In general, it might be assumed that AVs significantly benefit cities. However, the size and dimensions of their impact are still uncertain as they are still in pilot mode in some cities [7]. The present study tries to investigate this broad assumption by conducting a literature review on the possible implications of AVs in cities. To achieve this, a detailed study of the literature on the possible effects of AVs on vehicle ownership, parking spaces, land use patterns, and transportation modes, as well as a synthesis of AV use cases was conducted. The findings from this research outline:

- The potential benefits, challenges, and concerns related to the introduction of AVs;
- A synthesis of the results from AV uses cases;
- New research directions on impact assessments of AVs from the perspectives of existing use cases.

The remaining parts of the paper are arranged as follows. Section 2 explains the emergence of AVs. Section 3 describes vehicle ownership and mobility services in the era of AVs. Section 4 explains the potential impacts of AVs on transport modes, while Section 5 analyses the land use effects of AVs. In Section 6, a synthesis of AV-use cases is presented. Section 7 is dedicated to discussions on the findings, and finally, in Section 8, the conclusions of the study are reported.

2. The Emergence of AVs

2.1. Historical Antecendents of AVs

The concept of AV technologies has been outlined in science fiction and literature even before the invention of the car itself, which shows that it is not a purely contemporary invention as it may look as if. The history of AVs dates to the 15th century when Leonardo de Vinci sketched a self-propelled vehicle. The Institute and Museum of the History of Science in Florence made the decision in 2004 to reconstruct Leonardo's vehicle, and they eventually succeeded. Then, the idea of self-controlled vehicles appeared in both science fiction and literature, which might have played an important role in the current AVs we are talking about [8].

The first AV was prototyped approximately one hundred years ago, named "Linriccan Wonder", and tested in New York City, USA in 1926 by Houdina Radio Control. As shown in **Error! Reference source not found.** [9]"Linriccan Wonder" was equipped with an antenna on its rearmost compartment and ran by another vehicle following it and sending a radio signal that got caught and sent to the circuit breaker. In the same year, in December 1926, a new car named "Phantom Auto", which is a modified version of the "Linriccan Wonder", was demonstrated by Achen Motors in Milwaukee, USA [10].

Figure 2. Remote-controlled vehicle by Houdina.

The study by Bimbraw [10] outlined that General Motors advanced the system under the name "Futurama" and showed it at the world's fair in 1939 that had a circuit entrenched in the road and managed by radio, similarly to the prior versions. As explained by Bimbraw, the advancement in AV technologies emerged in the 1950s and 1960s. A miniature car was built by the RCA lab in 1953 and the idea was scaled-up and tested on the highway, which has a series of detector circuits in 1958 by Leland Hancock in Lincoln Neb. Bimbraw also added that since then, especially in the 1960s, General Motors accomplished several experiments incorporating electronic guide systems, and more advancements in this technology have been recorded; the one developed by Ohio State University which interacted with electronic devices embedded in the highway was one of the achievements.

Another study by Tsugawa [11] indicated that in Japan, AV technologies in the form of an automated highway system started in the Mechanical Engineering Laboratory in the 1960s with the influence of the USA. The system had an embedded inductive cable under the roadway and a pair of pickup cables for lateral control. The vehicle had a collision-avoidance system and cooperative functions which allowed communication between the vehicle and the infrastructure. In the same decade, Bimbraw [10] stated the UK's Transport and Research Lab introduced AV technology that could interact with magnetic cables under the road surface and drive at 130 km/h with a constant speed and direction in all-weather settings.

In the 1970s, in Japan, a vision-based system was introduced that enhanced the technology of AVs. In 1978, hardware logic was used to process the video signal and it drove up to 30 km/h on a test track. One decade later, in the 1980s, dead-reckoning systems were integrated into the vision-based automated vehicle system that drives up to 10 km/h while evading fixed obstacles [11]. Similarly, the vision-based system was also experimented on a test roadway with no other traffic in Munich, Germany, and achieved a speed of 63

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km/h. In the 1990s, the Autonomous Land Vehicle project in the USA tested AVs that used computer vision, light detection and ranging, and autonomous control to direct a robot vehicle that drove up to 31 km/h [10]. Besides, in Japan in the 1990s, a new system that allows V2V communication for automated platooning was started. In 2000, a cooperative driving system with five AVs was developed and was able to drive 50 to 60 km/h on the test track with lane changing and flexible platooning scenarios [11]. According to the study by Anderson et al. [12], the momentous development of AVs attained between 1980 and 2003, which is considered the first phase in the trend of developmental gain, required researchers to put foundations on two important aspects of the technology: on the one hand, improving the transport infrastructure and on the other hand, working on fully autonomous AVs that are independent of the infrastructure. At the same study, it is explained that the second phase of AV technologies advancement is from 2003 to 2007, remarkedly enhanced by the "Grand Challenge" organized by the US DARPA. The authors highlighted that the DARPA challenge included an off-road race of AVs that gets a better understanding in society as well as from the companies, such as Google, Audi, and Toyota. The race progressed into urban areas where the AVs should drive under mixed traffic conditions, obeying the traffic rules, which gives an insight into the necessity of improvement in the sensor technology to recognize non-AVs, road markings, and traffic signs and obey other traffic rules as pointed out by the authors. Besides, as explained by Faisal et al. [13] Volvo began its journey toward AVs in 2006, and level 5 AVs were introduced in 2017. In addition, Google completed a three-million-mile journey across four US states just in 2017. Tesla model vehicles are now equipped with automated driving technologies and play an important part in the transition to AVs with a high level of automation. Furthermore, OEMs, such as Mercedes-Benz, Nissan, Audi, and BMW are attempting to bring AVs to market.

2.2. Terms, Definitions and Standardization

Nowadays, urban roads are populated with vehicles equipped with ADAS, which is a vehicle technology that provides a safe human-machine interaction by employing technologies (e.g., cameras and sensors) to recognize surrounding or driving faults and take appropriate action [14]. Recently, in July 2022, the new EU regulations on vehicle safety and automated vehicles also outlined that cars and vans should be equipped with lane keeping assistance, automatic emergency braking, and an event data recorder [15]. Furthermore, the technologies of AVs are evolving from the cruise control system, whose main purpose is to maintain the speed set by the driver, which has further progressed into ACC and CACC systems. The first has the functionality to control the acceleration of the vehicles by taking the space headway and speed difference between the following and preceding vehicles into account, while the second encompasses V2V communication capabilities [16]. CAV technologies, furthermore, have been advancing and are promising to alleviate the current challenges of road transportation. **Error! Reference source not found.** depicts the definitions and categories of vehicle automation and connectivity signposting, that AVs are the cornerstone of the road toward connected and automated urban mobility systems [16].

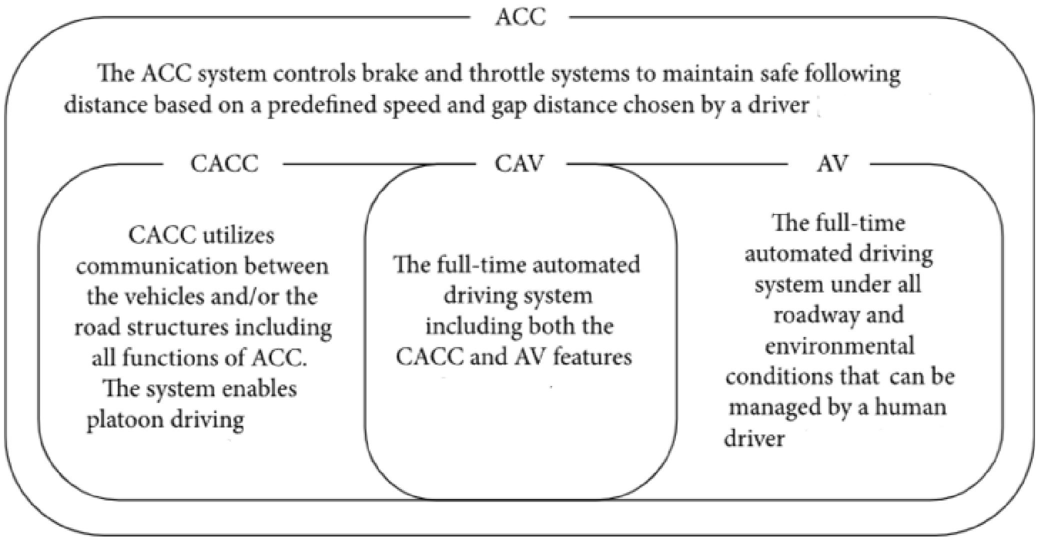

Figure 3. Definitions of vehicle automation and their categories.

The names used to describe automated driving systems in vehicles have varied among stakeholders in the field. The basic goal underlying vehicle automation is to replace human sensory functions with technology; the human role is decreased and replaced by machines and algorithms that can execute all or portions of the dynamic driving tasks. However, several names and terms have been used for vehicles with automation capability. 'Driverless' (e.g., [17]), 'self-driving' (e.g., [8]), 'autonomous' (e.g. [9], [18–20]) and 'automated' (e.g. [4], [21–24]) are common terms used to describe automated driving systems. The first three names refer to fully automated vehicles and do not require any human driver interference. However, the term 'automated vehicle' refers to a vehicle system that can have control at a variety of levels and does not need to be fully automated, with no human driver intervention under all conditions [25].

Autonomous vehicles are vehicles that "can sense their local environment, classifying the types of objects that they detect, reasoning about the evolution of the environment and planning complex motions that obey the relevant rules of the road" as defined by Campbell et al. [26] and the meaning infers that they are self-sufficient and independent. If vehicles need communication or cooperation with outside entities, they should not be called autonomous. On the other hand, AVs are characterized as vehicles that can execute the dynamic driving task themselves without or with limited human driver assistance [27]. Hence, AVs could include vehicles with communication capabilities, such as V2V, V2I, V2N, and even V2P. The general term for all those communication features is Vehicle to Everything, or V2X. AVs are also referred to as cooperative or connected. Nevertheless, all connected vehicles may not be referred to as AVs, as conventional vehicles can also be connected. AVs do not need to be connected or communicate with other entities, even if they will do so to gather additional information for their decision. The communication feature in AVs is not just to exchange information but to achieve a common goal, such as safety and efficiency. In this case, the phrase "cooperative automated vehicles" is the preferable name for the technology [28]. Above and beyond, a briefing from the European Parliamentary Research Service defines the three terms related to automation and connectivity as follows [29]:

- Automated vehicles are "vehicles equipped with advanced technology that can help the driver or intervene in some of the driving functions."
- Autonomous vehicles are "vehicles that are completely automated and can perform all the driving tasks with no human interference."
- Connected vehicles are "vehicles equipped with advanced devices to exchange information with other vehicles or the infrastructure through the internet."

Generally, looking at the works of literature (e.g. [22,30,31]), fully AVs can be grouped into two categories: autonomous AVs and connected/cooperative AVs. Autonomous AVs are vehicles that conduct the driving task depending solely on their sensors, while connected and cooperative AVs can use their communication capabilities to augment the information acquired by their sensors.

The standardization and taxonomy of AVs have been an issue throughout their evolution; many entities have defined their levels of automation in the last decade. BASt defined five levels of automation, considering the levels of human driver involvement and the range of speed in the driving processes. The levels are: "driver only", "assistance", "partial automation", "high automation", and 'full automation". While the first three levels apply to all road types and speeds, the latter two are exclusive to high-speed motorways [32]. Similarly, the US NHTSA adopted five levels of automation as follows: "no automation", "function-specific automation", "combined function automation", "limited self-driving automation", and "full self-driving automation" [33]. Currently, the taxonomy provided by the SAE International is the most used classification of AVs in research as it is a global association, as well as provides a clear boundary in the level of automation. SAE endorsed the term "automated vehicles" to avoid misleading definitions and terms and defined six levels of driving automation based on driving task allocation between the human driver and the driving automation system, which are somehow like NHTSA. The main difference between the two is that SAE defined two independent levels (level 4 and level 5) to separate levels that the one does not require the driver's intervention and those fully independent of the system. For the first three SAE levels, the human driver is the one who controls the main driving processes, and the vehicle system provides only driving support. From levels 3 to 5, the vehicle system performs the main driving processes [27] shown in **Error! Reference source not found.** [34].

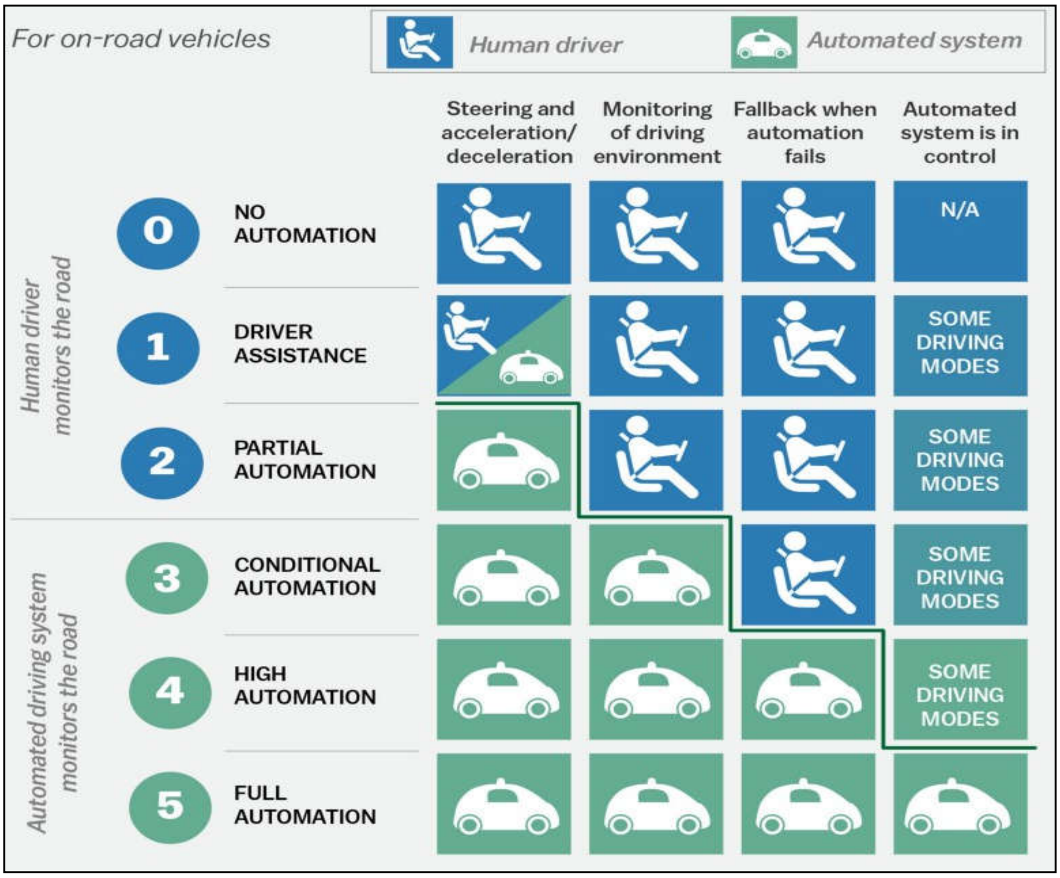

Figure 4. Driving automation levels as recommended by SAE.

3. Ownership, Mobility Services and AVs

In 2020, Neckermann and John [9] explored the possible business models of future mobility with AVs and outlined that automation of the mobility system will bring a new ownership scenario that encourages shared uses of AVs. They explained that AVs will bring numerous benefits beyond transportation (Mobility+) as they could be used, for example, as hotels where people take a rest while travelling from one city to another or within a city, as driving is not important anymore and AVs could be a competitor in the hotel industry. The authors pointed out that by cooperating with other business companies (e.g., Amazon), AVs could also be used as a place to sell a service. They also added AVs will be a good opportunity in medical transport even though the user will be resisting this type of service, as sharing AVs for sick people might not be appropriate.

Another thought-provoking study conducted in 2021 by Chen et al. [35] who analyzed the cost and business model of shared AVs, outlining that automated driving packages, the internet of things, and service suppliers are new shareholders in the development of mobility services in the era of automated transport, which links vehicle owners, OEMs, parking, and fleet operators. The authors highlighted that through P2P AV-sharing business models, the AV owner will get more than a 20% operational cost reduction compared to the traditional car-sharing system since the technological advancements will result in a price drop of automated driving software packages as well as a reduction of parking-related fees and effectively increasing parking use. They also stated the existing car-sharing services with B2C models, station-based or free-floating, could be dominated by AVs adding the technology will bring job opportunities for citizens.

In their study conducted in 2021, Silva et al. [36] explained that the introduction of AVs to cities requires the revision of the existing mobility service and the corresponding business model to get the most out of this technology. Their results revealed that as no human driving ability is needed anymore for AVs, taxi and ride-sourcing services will be replaced with ridesharing, P2P car sharing, or a new business model, where MaaS becomes in charge of the business and market operations. Furthermore, the authors highlighted that an AV-based shared mobility system needs a strong bond among owners, operators, and service providers. However, the result of a study by Mohammadzadeh [37] discovered that vehicle ownership is socioeconomic status and a subjective identity in the society of automobiles. Based on the author's argument, AVs must be judged as a technological revolution instead of the general theory that shared AVs will certainly substitute private ownership because owning a vehicle has been emblematic in society. Their results revealed that 63% of 192 respondents in Auckland, New Zealand have a preference to own an AV over shared options, irrespective of the cost.

Recently, in 2022, Camps-Aragó et al. [38] assessed the policy aspects and business models for sustainable adoption of AVs in Brussels and Flanders, Belgium, and highlighted that MaaS is substantial to integrate AVs with non-AVs based mobility services via a business ecosystem including public authorities, OEMs, research institutes, and users. They strongly suggested that public transport operators, as they can anchor and create cooperation among national and international enterprises that accelerate the adoption of AVs, should take the lead in MaaS developments. Moreover, the authors concluded that policies that encourage data sharing, funds for pilot projects, and the provision of tools for the cooperation of stakeholders are noteworthy in the adoption of AV-based mobility services in Belgium.

4. Transport Modes and AVs

The revolution in vehicle automation has had a significant impact on urban mobility. More importantly, how the introduction of AVs will affect active mobility options such as walking and bicycling, as well as public transportation, is the main concern to be explored.

4.1. Active Mobilities

Walking and cycling are the most sustainable modes of transportation, having little or no negative impact on other travelers, zero-emission, zero-fuel consumption, and being healthy, sociable, affordable, and accessible to the majority of people [39]. Here, the impacts of AVs on active mobilities can be explained by their relationship with concepts of "chrono-urbanism", which is an alternative way of life in cities where the inhabitants can access services and amenities independent of cars by walking or cycling. 15-minute, 20-minute, and 30-minute cities are categorized under the chrono-urbanism concept, which means the basic urban functions can be accessed within the respective distances. This urban planning philosophy plays a key role in the sustainability and resilience of cities, especially during pandemics like COVID-19 [40]. Assessing the effects and implications of AVs on active mobility, such as walking and cycling, will thus provide planners with new insights into the development of smart, sustainable, and resilient cities.

Booth et al. [41] presented the implications of AVs on active mobility users in urban areas via an online questionnaire covering 1624 respondents in Australia, and their findings show that AVs are expected to replace a significant number of active mobility modes, with 18% and 32% will replace their walking and cycling trips, respectively. They also stated that the Z generation (younger age group) and those who are optimistic about vehicle automation and the high rate of active mobility users will be the ones to switch from cycling and walking to AVs, resulting in a deterring impact on active mobility systems overall.

In 2021, Pettigrew [41] conducted interview-based research to investigate the impacts of AVs on walking in four regions: Australia, the European Union, the UK, and the USA. The author interviewed 44 stakeholders in various sectors, including health, customer representative initiations, and transportation, on the different impacts of AVs on walking behavior, and the findings revealed that the impacts of AVs on walking are unknown until further developments are realized and users get experience with the technology. Nevertheless, the author highlighted that walking interest will be negatively impacted in the early stage of transforming conventional transport to AV-based mobility services; thus, proactive policies and strategies are necessary to reduce sedentary activities that may occur as a result of vehicle automation.

Another study in 2021 by Eichholz et al. [21] explored the individual stress and uncertainty of cyclists while driving on different roadway infrastructures via a questionnaire-based study. According to their findings, 90% of 337 respondents showed the appearance of AVs would affect their safety feelings when they drive on the same infrastructure. They outlined that AVs should have the same appearance as conventional vehicles and should keep a safe distance and speed while following and overtaking so that the cyclists feel safe, and the level of uncertainty is reduced. AVs could significantly improve the safety of cyclists if they reached 100% of the market penetration level. However, in comparison to the current situation, the mixing of AVs with conventional vehicles will increase the individual stress and uncertainty sense of cyclists.

4.2 Public Transportation

In 2019, Abe [42] quantified the potential impacts of automated buses and automated taxis in Japanese cities and indicated the cost of public transit can be reduced due to vehicle automation, and the results designated those automated buses could significantly benefit the public transportation industry, whereas automated taxis can benefit (e.g., cost reduction) both residents and transit operators. The authors also added that the benefits from vehicle automation are higher in taxis than in buses and mentioned that operation costs are reduced by 44-66% for taxi-based trips and 13-37% for bus-based trips with taxi access is forecasted.

In 2020, Othman [43] presented the prospects of a future public transport system, in which AVs are introduced in cities. The author outlined four implementation strategies that are possible in future urban transportation. The first case is AVs can be a competitor of public transport systems both in the form of private usage and shared mobility services. In the second scenario, AVs can be owned by public transport operators and integrated into public transit services as first and last-mile solutions. The third case is the development of automated buses, and lastly, the integration of AVs with automated buses in which shared automated buses can be used as first and last-mile on-demand services to sustenance the public transit system, and later the transit network can be switched from conventional to automated public transport. The authors concluded that AVs would bring the benefit to create a mobility ecosystem that integrates different transport modes including both AVs and non-AVs.

Csiszár and Zarkeshev [44] developed a new service type called "automated random transportation system" which picks up users based on the capacity of the shuttle at specified routes in Budapest, Hungary. Their proposed system has designated stops between defined origins and destinations and the users reserve a seat, declaring the origin and destination stops. The decision-making server, which can be operated by the transport operator, decides whether the vehicle needs to stop at intermediate stops based on the information collected about the passenger and the vehicle capacity. Besides, the authors concluded that the introduction of AVs as public transport results in a reduction of idle cost and idle time through their technological benefit when integrated into the traditional public transport system.

A study by Bischoff and Maciejewski [45] focused on the city-wide replacement of private conventional vehicles with automated taxis in Berlin, Germany, and highlighted that a 100,000 AV fleet could be enough for Berlin, which means one AV can replace the travel demand served by 10 private conventional vehicles. Nonetheless, the authors identified that more than one automated taxi is needed to replace a smaller number of conventional vehicles in cities with sprawled development than in densely populated urban centers.

In 2020, Sun et al. [46] examined the use of an integrated public transport system in Singapore that serves both passengers and goods, which is supported by advancements in vehicle technologies. Their findings highlighted new vehicle design concepts that can be used for passengers and goods, which is important to reduce the negative externalities of urban transport and logistics and highlighted that government policies and strategies will have a paramount role in the realization of this system. The authors also stated that novel vehicle design concepts such as movable seats would help to drive the trend of introducing automated public transit in cities.

5. Land Use and AVs

AVs will have significant impacts on the spatial elements (e.g., roadway, parking, and public space) of urban areas such as parking space and land use pattern that could show the necessity of urban spaces repurposing in cities.

5.1. Parking Space

The study by Siqueira Silva et al. [19] investigated the impacts of AVs on parking spaces for a district in Budapest, Hungary considering the existing parking scenarios and hypothetical market penetration. They built scenarios consisting of private ownership and shared AVs with varying market penetration rates and occupancy types: single and multiple. Their findings pointed out, that currently, 5% of the total area of the studied districts is used for parking and outlined that shared AVs could reduce the parking demand more efficiently than private AVs. When the market share reaches 100% shared AVs with multiple occupancies, 4.5% of the parking spaces can be saved and can be repurposed for active mobility solutions (e.g., 12,000 bicycle docking stations). 100% single occupancy shared AVs can save 4.2% of spaces, however, they highlighted that only 0.5% of parking space can be saved when AVs will be owned and used privately.

The study by Zhang and Guhathakurta [47], using discrete event simulation, explored the parking space requirements of shared AVs in Atlanta, the USA assuming that shared AVs can cover 5% of the trip within the region. They highlighted that parking fee has an impact on the demand for parking and considered free parking and charged parking scenarios. According to their findings, 4.5% of parking spaces can be saved when 5% of the trip is served with shared AVs due to a reduction in private vehicle ownership and improvement of vehicle use efficiency. They also quoted, that when there is a parking charge, the parking demand will move from urban centers to peripheral and low-income community neighborhoods, which results in a question of social equity. Similarly, in 2020, Zhang and Wang [4] conducted a city-wide agent-based simulation to estimate the trajectories of parking demand in the era of shared AVs in the same city, Atlanta considering various market penetration levels of four mobility scenarios: private AVs, shared AVs, private conventional vehicles, and shared conventional vehicles. Their simulation results revealed the shifting of parking demand from commercial areas to residential and mixed-use areas and signposted the introduction of AVs resulted in a reduction of off-street parking demand and an upsurging of curbside loading/unloading demand. With AVs market penetration of 34% (70% private and 30% shared uses) and implementation of demand-responsive transport, the authors expected a 20% reduction in parking demand in inner cities; however, demand will double in residential areas, and the number of empty vehicles on the road will increase. Besides, the study by Nourinejad et al. [48] stated the demand for parking spaces could be reduced by up to 87%.

In 2020, Azevedo et al. [49] conducted intriguing research in which they analyzed alternative parking methods using coordinated parking systems in high-density parking (garage) situations of low-level private AVs in San Francisco, USA. According to the findings, vehicle automation can save parking space by 50% while also improving access time while entering and exiting the parking lot. Another study by Millard-Ball [50] conducted for the parking situation in downtown San Francisco, USA, using a microscopic traffic simulator called SUMO, investigated the challenges of private AVs on parking spaces, taking parking fees into account, and demonstrated that the increase in parking fees will result in more vehicular traffic in the dense and inner cities. The author also stated that the parking demand will be reduced by double. However, this could increase congestion and vehicle mile travelled as private AVs will cruise, return home, or search for low-fee parking spots.

In 2021, Kumakoshi [20] compared the parking demand of shared AVs with the existing state of private vehicles via a traffic simulation. 100% shared AVs were assumed for the study location, which is Okinawa, Japan. The output of their study revealed that 94% of the total parking space can be saved, and they outlined that more space-saving is possible in the outskirts (> 94%) than in the inner city (70-90%). Regarding the connection between land use and parking demand, they added that more parking space can be saved in office-dominated zones than in residential zones. Another intriguing study conducted in 2021 by Winter et al. [23] presented a simulation study demonstrated that shared AVs in Amsterdam, the Netherlands will result in parking demand reductions and encourages even use of parking spaces throughout the city; however, empty vehicle mile travel and undesired service externalities such as congestion and energy consumption are predictable.

5.2. Land Use Patterns

Kang and Kim [51] estimated the influence of AVs' introduction on land-use change in Seoul, Korea. They found that the introduction of AVs resulted in land-use changes from agricultural to residential areas on the outskirts of the city, increasing suburbanization; AVs will improve accessibility in central commercial districts and residential areas as individuals can reside, work, and shop at greater distance since driving is not a concern in the era of AVs. They added that when the market penetration of AVs increases and shared AVs and integrated mobility systems with AVs are encouraged, commercial to residential land-use change is anticipated.

Riggs et al. [52] investigated the impacts of AVs on streets from a design standpoint. They outlined, to improve urban space livability in the era of AVs, four basic principles of street planning and policy recommendations: a) On-street parking can be reduced as AVs promote MaaS and shared vehicle use; b) roadway width can be reduced as AVs can drive more closely due to a significant reduction in human error that can occur in conventional vehicles; c) the reduced roadway width can be repurposed to active mobility facilities such as bike lanes and footpaths; d) additional smart infrastructures, such as facilities that capture real-time data and support for electrification.

Another study by Riggs et al. [53], conversely to the aforementioned studies, found that there is a danger in cities as the current scenario will end up dedicating more spaces to AVs and the quality of walkability will be reduced as some cities like, New York, has worked on strategies that encourage the dedication of spaces for private-owned AVs. To overcome this, the authors proposed planning and design principles that focus on people-centric solutions. They outlined three main principles for creating walkable urban space in the era of AVs: encouraging shared mobility; calming traffic in residential and commercial business districts; and supporting the decision through land-use planning strategies to fill underutilized spaces and control the power of sprawling caused by AVs.

6. Synthesizing Selected Use Cases

Among pilots, including both completed and ongoing, thirteen European use cases have been selected for further synthesizing. During the selection process, the geo-graphical location of the use cases, the type of vehicle used, the weather conditions, and the availability of published results from the pilot have been considered. To synthesize the selected use-cases, five dimensions have been considered. These are roadway conditions, vehicle type, type of transport service, traffic conditions, and the participants as depicted in **Error! Reference source not found.**.

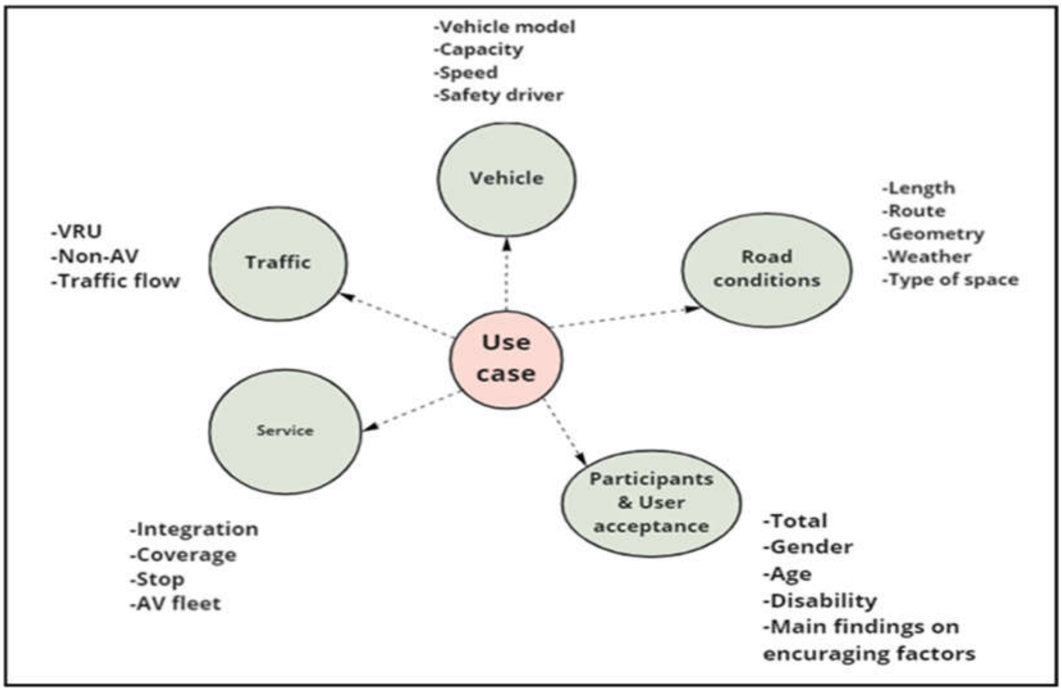

Figure 5. Dimensions of the use cases for synthesizing.

The synthesis scenario includes thirteen use cases in eight cities, and a code is provided for each of them as shown in Table 1. Some of the works of literature talk about the same use cases of AVs in the same pilot project but conducted at various times (e.g., P1). In this case, both works of literature are considered in the same category. On the other hand, the studies (e.g. [54]) investigated two or three use cases (e.g., P3, P4, P5) in their study. Thus, they are considered separately.

Table 1. Use case coding and its location

Code	Location of use case	Reference
P1	Greenwich, London, UK	[55,56]
P2	Espoo, Helsinki, Finland	[57]
P3	Helsinki &Lapland, Finland	[54]
P4	Helsinki & Lapland, Finland	
P5	Helsinki & Lapland, Finland	
P6	Berlin-Schoenberg, Germany	[58–60]
P7	Berlin-Schoenberg, Germany	
P8	Brussels Capital Region, Belgium	[61]
P9	Brussels Capital Region, Belgium	
P10	Lyon, France	[62]
P11	Oslo, Norway	[63]
P12	Bad Birnbach, Germany	[64]
P13	Salzburg, Austria	[65]

6.1. Roadway Conditions

The road condition has an important implication in the operation and design domain of AVs. Table 2 presents the different road conditions of the selected use cases and shows that the length of the roadway section used in the pilots ranges from 150 m to 3.4 km. The locations of most of the pilots were on a fixed route and shared spaces on campus, in parks, or in a city that has a variety of geometric characteristics ranging from straight lines to unsignalized intersections and roundabouts. Furthermore, in use cases conducted in Nordic countries (Finland and Norway), the users have experienced AVs in adverse weather conditions such as heavy rain and snow.

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Table 2. Road conditions in selected use cases

Code	Length (km)	Type of space	Route	Weather	Geometry	Reference
P1	3.40	Shared	Fixed	All-weather	Curves and intersections	[55]
P2	0.70	Shared	Fixed	Snow, heavy rain	Intersections	[57]
P3	2.00	Shared	Fixed	Heavy winter	Pedestrian crossing, roundabout	[54,60]
P4	0.70	Shared	Fixed	Summer	Intersection	[55]
P5	1.30	Shared	Fixed	Heavy winter	n.s.	
P6	0.70	Shared	Fixed	n.s.	n.s.	[58]
P7	1.50	Shared	Fixed	n.s.	n.s.	[60]
P8	1.50	Shared	Fixed	Summer	Curve, crossings	[61]
P9	0.35	Shared	Fixed	Autumn	Intersection, curves	
P10	2.50	Shared	Flexible	n.s.	Different characteristics	[62]
P11	1.50	Shared	Fixed	Winter	Different characteristics	[66]
P12	8min	Shared	Fixed	n.s.	Simulated environment	[64]
P13	0.15	Closed	Fixed	Autumn	n.s.	[65]

* min: the route was an 8-minute drive; n.s: not specified.

6.2. Vehicles

Table 3 presents the characteristics of the vehicle in the use cases, including the vehicle manufacturer, operating speed, capacity, and the availability of a safety driver. In the selected use cases, six diverse types of AVs have been used. EasyMile and Navya are the most used models, followed by Sensible 4, Local Motors, Ruter, and the vehicle developed by Westfield Sportscars & Heathrow Enterprises. The maximum operating speed reached in all the synthesized use cases is 18 km/h in Helsinki (P3) and Oslo (P11). The maximum number of passengers in the vehicle also varies among the considered pilots. The minimum is one, with Sensible 4 in Finland. In P13, in Salzburg, a crowded scenario has been considered in a closed-roadway testing environment with the idea of assessing users' attitudes toward AVs in different mobility scenarios. Furthermore, remote control mode of safety driver is used in P13 while ten of the use cases have an onboard safety driver, and a hidden steward was present for use case P7 in Berlin.

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Table 3. Vehicle characteristics in the selected use cases

Code	Developer	Max. operating speed (km/h)	Capacity	Safety driver	Reference
P1	WSH	15	4	Onboard	[55]
P2	EasyMile	12	10	Onboard	[57]
P3	Navya	18	8	Onboard	
P4	EasyMile	12	10	Onboard	[54]
P5	Sensible 4	n.s.	1	Onboard	
P6	Local Motors	8*	12	Onboard	[58]
P7	EasyMile	13	10	Hidden	[60]
P8	EasyMile	15	8-12	Onboard	[61]
P9	EasyMile	15	8-12	Onboard	
P10	Navya	n.s.	15	n.s.	[62]
P11	Ruter	18	9	Onboard	[63]
P12	EasyMile	12	7	Onboard	[64]
P13	EasyMile	n.s.	crowded	Remote	[65]

WSH: Westfield Sportscars &Heathrow Enterprises; *: average; n.s.: not specified.

6.3. Services

The main aims of all the use cases are to create public awareness for large-scale introductions of AVs. The AVs in three of the use cases are used as feeders to conventional PT. The pilots in Finland (P3) and Lyon (P10) replaced the existing PT lines. A single vehicle is used in most of the use cases during the specified time shown in **Table 4**. The maximum vehicle fleet in the use cases is 4 in P1 (London).

Table 4. Services characteristics in the selected use cases

Code	Integration	Coverage	No of stops	No of AVs	Time	Reference
P1	Feeder	Single line	4	4	Winter, 2018	[55,56]
P2	Feeder	Single line	n.s.	1	Oct -Nov 2017	[57]
P3	Replacing PT	Single line	n.s.	1	May-Oct 2018	
P4	n.s.	Single line	n.s.	1	May – Jun 2018	[54]
P5	n.s.	Single line	n.s.	1	Oct 2018	
P6	Within a campus	Single line	n.s.	1	Mar & Jul 2017	[58]
P7	Within a campus	Single line	n.s.	1	n.s.	[60]
P8	No	Single line	5	n.s.	Jun-Sept 2019	[61]
P9	No	Single line	n.s.	1	Aug-Oct 2019	
P10	Replacing PT	Single line	n.s.	2	May 2018	[62]
P11	Feeder	Single line	n.s.	1	Jan - Feb 2020	[63]
P12	No	Single line	4	1	Oct 2017	[64]
P13	No	Single line	n.s.	1	Sept 2019	[65]

n.s.: not specified

6.4. Traffic Conditions

Road traffic dynamics have a significant impact on the introduction of AVs to urban roads. The interaction between AVs and non-AVs as well as VRUs, such as pedestrians and cyclists, is among the determinant factors of AVs' adoption. As presented in Table 5, ten use cases have tested AVs in public spaces shared by VRU. P13 (Salzburg) was conducted on a closed road with no access to VRUs. Regarding the traffic flow, P3 and P4 (Helsinki and Lapland) as well as P9 (Brussels) considered a mixed traffic flow where AVs shared the same lane with non-AVs. However, in the other use cases, it was either a dedicated lane or it had not been specified.

Table 5. Traffic characteristics on the test sites of selected use cases

Code	VRUs	Non-AVs	Traffic flow	Reference
P1	Yes	Yes	Dedicated lane	[55]
P2	n.s.	Yes	n.s.	[57]
P3	n.s.	Yes	Mixed	
P4	Yes	Yes	Mixed	[54]
P5	n.s.	n.s.	n.s.	
P6	Yes	Yes (car, truck)	n.s.	[58]
P7	Yes	n.s.	n.s.	[60]
P8	Yes	No	Dedicated lane	[61]
P9	Yes	n.s.	Mixed	
P10	Yes	Yes (car, truck)	Dedicated lane	[62]
P11	Yes	Yes	n.s.	[63]
P12	Yes	No	n.s.	[64]
P13	No	No	Dedicated lane	[65]

n.s.: not specified

6.5. Participants (users)

Demography is one of the factors with a significant impact on the acceptability of AV in cities. As shown in Table 6, gender, age group and disability are among the main demography considerations in the use cases. The total number of participants in the survey ranges from sixteen in P13 (Salzburg) to 384 in P8 (Brussels). However, it should be cited that the total number of participants mentioned does not consider the participants in the whole duration of the pilot but the number of participants in the considered report. The introduction of AVs brings a substantial benefit to mobility disadvantaged populations, such as the elderly and disabled individuals and most pilots consider the elderly population. However, disabled individuals have taken part in only four of the use cases, and other use cases have not considered them, or their presence has not been mentioned in the report.

Table 6. Demography of participants in the selected use cases

Code	Total	Male (%)	Female (%)	Disability	Age range	Reference
P1	65	55	45	n.s.	18 -72	[56]
P2	44	54.5	45.5	Yes	15-64	[57]
P3	141	61	38	Yes	15-74+	
P4	70	56	43	Yes	15-74+	[54]
P5	70	56	43	Yes	21-60	
P6	30	80	20	n.s.	19-75	[58]
P7	119	60	34	n.s.	17-91	[60]
P8	384	48	52	n.s.	15-65+	[61]
P9	145	43	57	n.s.	n.s.	
P10	36	50	50	Yes	15-74	[62]
P11	25	28	72	No	<35 & >58	[63]
P12	24	79	21	n.s.	21-70	[64]
P13	16	19	81	n.s.	21-60	[65]

Table 7 presents the summary of concluding remarks on the encouraging factors of AV adoption. Overall, the findings revealed that perceived safety, trust in technology, and the potential benefit of AVs to improve the urban mobility services are the most determinant factors in a large-scale deployment of AVs.

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Table 7. Summary of remarks on encouraging factors of AVs' adoption

Code	Concluding remarks	Reference
P1	Enhancing the safety of VRU and awareness about the technology.	[56]
P2	Increasing users' familiarity with automated rail transport systems. Use of AV with demand responsiveness and flexible route services.	[57]
P3 P4 P5	Increase public exposure to positive real-world experience in the pilots. Secured, trustfulness, and safe. Heavy winter has no impact AVs acceptance.	[54]
P6	Potential to improve mobility services, safety driver involvement (either remote or onboard), and use of AVs as a feeder service to PT.	[58]
P7	Dedicated lane, V2X communication, same appearance with non-AVs	[60]
P8 P9	Trustfulness, experience in different urban settings (e.g., complex traffic), and improving speed, safety, and security	[61]
P10	Micro-transit as a last/first-mile service integrated as multimodal services, im-proving technology reliability and cybersecurity, and increasing operating speed.	[62]
P11	Inclusiveness to mobility disadvantaged individuals, the presence of onboard safety driver, and increasing operation speed and smooth driving.	[63]
P12	Increasing operation speed, smooth maneuvering, and enhancing external human-machine interfaces.	[64]
P13	Trustfulness, availability of safety driver (onboard or remote), and safety	[65]

7. Discussion

The current study shows that AVs are expected to be introduced in a near future, bringing both benefits and concerns; the advancements in computer science and information communication technology have fueled the emergence of this disruptive mobility technology to cities. However, issues related with regulatory, and standardizations has been the main concerns in the way towards automated mobility system. For example, considering the terms used to describe vehicles with automation capability, different names such as self-driving, autonomous, and automated have been used in the works of the literature that would have a deterring impact in the standardizations of AVs for large-scale deployment. This study has been consistent with the term 'automated vehicles' as this term is widely adopted both in the academia and the industry. This study considers a comprehensive literature review on its impact on vehicle ownership and mobility services, traditional transport modes and land use. Furthermore, 13 AV use cases located in the European region have been synthesized for analyzing the trends of deployments of AVs in cities.

The results from the reviewed literature showed that AVs are anticipated as a technology as utopian and dreaded elements in future city as presented. Regarding the ownership and mobility services, the results from the literature revealed that shared uses and on-demand transport systems are the most expected urban mobility services that will bring new business models to use the most out of vehicle automation. Ridesharing, P2P car-sharing, and B2C will be the dominant service models in the era of an AV-dominated urban environment. AVs could also bring new services such as the use of the vehicles for services other than mobility such as a place to rest like a moving hotel as suggested by Neckermann and John [9]. Besides, as also indicated in the study [36], it should be emphasized that the MaaS ecosystem plays a key role in the realization of the expected benefits of AVs including reducing energy consumption and emissions as well as providing efficient mobility management through the concept of multimodality, intermodality, and interoperability.

Regarding the findings in the literature considering the impacts of AVs on public transportation and active mobility, the findings from the literature highlight the introduction of AVs into the urban mobility system will bring a modal shift as well as a change in travel demand and travel patterns in cities. Future urban mobility in the era of AVs could bring an innovative mobility ecosystem supported by co-creation and a disruptive business ecosystem. As a result, in works of literature focusing on the mobility impacts of vehicle automation, shared uses of AVs in the form of taxis, ridesharing, or automated buses are expected. Nevertheless, the potential influence of AVs on active mobilities (cycling and walking) is still uncertain.

Results from studies focusing on the spatial impacts of vehicle automation pointed out that the impacts of this disruptive transport technology can improve the quality of urban spaces, albeit the extent of the impacts is still unknown. Besides, the spatial impact of AVs is highly dependent on the type of mobility services implemented in future cities. The more use of shared mobility, the more benefit is captured from AVs. It can be noted that AVs could reduce the demand for parking spaces and improve the roadway capacity in cities. However, the mixed-use of AVs with the conventional vehicles as well as vehicles with different automation levels could put a burden on urban spaces as their capability could not be easily identified by VRUs. This may imply the need for space segregation for AV users and non-AV users.

Currently, most of the pilots are conducted in controlled environments such as university campuses, parks, or other parts of the city with a controlled traffic setting. The results from thirteen synthesized use cases showed that, currently, stakeholders have focused on the shared uses of AVs, in which the pilots aim to create public awareness of the technology. The maximum road length for the investigated pilot projects is 3.4 km in London (UK), while several of them cover less than a kilometer. The AVs tested in the use cases show that the technology is capable of traversing different roadway conditions such as unsignalized intersections, pedestrian crossings, and roundabouts, as well as adverse weather conditions, especially for pilots located in Finland and Norway. Considering the vehicle categories, Navya and EasyMile shuttles with a capacity in the range of 8 to 12 and a maximum operating speed of 12 to 18 km/h with an onboard steward, on a dedicated lane and interacting with VRUs and non-AVs are the most common in the European region. Though it is not possible to provide a strong conclusion on the type of services provided with AVs in the use cases as they cover a short length of routes, the trend of the services with AVs is feeder services connecting main urban amenities with public transport hubs. The participants in the AV pilot stated that the low-operational speed is the most concerning factor in the use of these vehicles on their daily trips. Furthermore, the passengers outlined that better human-vehicle interaction and a similar appearance of AVs with non-AVs would increase their perceived safety.

8. Conclusions

Automated vehicles are today's automotive frontier, which has received an immense interest from urban planner and their large-scale deployment is expected in the close future. Because of their significant impact on the road transportation system, AVs have gotten more attention from car manufacturers, legislators, and researchers. Although there are uncertainties that require stakeholders' attention, the large body of literature assumes AVs could positively affect urban mobility and cities at large. The current study provides a literature review and synthesis of use cases of AVs to explore this broad assumption. To do so, a thorough review of the literature on the emergence of AVs and the potential implications of AVs on vehicle ownership and mobility services, active mobilities and public transportation as well as land use was done. Besides, 13 use cases of AVs are investigated from five dimensions: roadway conditions, vehicles, services, traffic conditions, and the participants (users).

The results revealed that although the introduction of AVs encourages shared mobility over privately used vehicles and this could bring a substantial benefit for cities, such as a reduction in parking demand and congestion, vehicle ownership has been a sociocultural identity in the history of the automobile. Thus, future cities could consider a new mobility ecosystem that can accommodate both private and shared mobility so that cities benefit most from the technology. Furthermore, the results showed that the implications of AVs on active mobility users such as cyclists and pedestrians could negatively impact the overall road traffic performance. Regarding the spatial impacts of AVs, vehicle automation is promising for effective use of public spaces, increased road capacity, and a reduction in parking space demand if shared-use AVs dominate the vehicle fleet. On the other hand, shared use of AVs has the potential to increase suburbanization eventually. In summary, AVs will bring a new mobility service that could significantly affect not just the mobility service-related issues but also other socioeconomics of residents, though the size of this impact is still uncertain.

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Nomenclature

Acronym	Description
AV	Automated Vehicle
ADAS	Advanced Driver Assistance Systems
VRU	Vulnerable Road User
US	United States
USA	United States of America
RCA	Radio Corporation of America
UK	United Kingdom
V2V	Vehicle-to-Vehicle
DARPA	Department of Defense Advanced Research Project Agency
OEM	Original Equipment Manufacturer
ACC	Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
CAV	Connected and Automated Vehicle
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrians or Passengers
V2X	Vehicle-to-Everything
BASt	German Federal Highway Research Institute
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
P2P	Peer-to-Peer
PT	Public Transportation
B2C	Business to Customer
MaaS	Mobility-as-a-Service
COVID	Coronavirus Disease

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