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Systematic Review

The Environmental Impacts of Automated Vehicles on Parking: A Systematic Review

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Abstract: Automated Vehicles (AVs) can drop off passengers at predetermined destinations and relocate to less expensive, remote parking facilities, which offers the potential to repurpose valuable urban land near activity centers for alternative uses beyond vehicle storage. While some researchers believe AVs are the core element to solving parking problems, relieving urban land use, and enabling low-emission travel, others contend that AVs could incentivize increased Vehicles Miles Traveled (VMT) and exacerbate congestion. To bridge these disparate perspectives, this study endeavors to elucidate the environmental ramifications of AVs on parking through a comprehensive literature review. Based on an initial sample of 299 retrieved papers, 52 studies were selected as the result of the selection criteria detailed in the paper. The selected papers were categorized into five gradual parts to answer the raised research questions. As a principal finding of this study, our research provides city planners, traffic operators, and scholars with full-picture insights and trustworthy guidance, emphasizing the pivotal role of AVs in deciphering the sustainable impact on the urban environment.

Keywords: automated vehicle; environmental impacts; parking; land use; VMT

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1. Introduction

Emerging technological advancements in sustainable transportation, targeting intelligent and environmentally friendly urban traffic, are advancing globally to diminish air pollution, improve road safety, alleviate traffic congestion, and enhance travel convenience [1–5]. Automated Vehicles (AVs) represent one of these solutions, and they are purported to create new opportunities for achieving green, safe, and smart mobility initiatives [6–8]. City planners, traffic operators, and scholars are increasingly focusing on the impacts of this innovative mobility solution [9–11].

Parking is a critical aspect of the urban transportation system that plays a fundamental role in shaping the mobility and accessibility of a city [12]. As cities continue to grow, the demand for parking spaces has escalated exponentially, leading to increased pressure on limited urban space and resources. Parking consumes a significant portion of space in automobile-oriented urban regions. Manville and Shoup estimated that about three-eighths of the central Los Angeles land area is occupied by parking [13]. According to the National Parking Association [14], the average cost associated with providing a parking space falls within the range of $5,000 to $50,000. Additionally, the inefficient utilization of parking spaces and the prevalence of unauthorized or illegal parking can exacerbate traffic congestion and hinder emergency services. Further, the growing environmental concerns associated with emissions from idling and circling for parking highlight the urgency to address parking issues in the context of modern transportation trends [15,16].

The emergence of AVs presents a paradigm shift in urban transportation, potentially transforming parking dynamics in cities [17] (see conceptual schematic in Figure 1). AVs can influence both the demand for parking spaces and the way parking facilities are designed and managed. On the one hand, AVs could increase the efficiency of parking by enabling better utilization of existing spaces through precise maneuvers and the ability to park in tighter spots. AVs can also reduce the need for immediate curbside access, as they can drop off passengers before proceeding to find parking further away, thus alleviating congestion in high-demand areas [18]. On the other hand, AVs may result in a surge in parking demand. As AVs become more accessible and affordable, individuals may prefer using AVs over traditional public transit, potentially leading to an increase in single-occupancy AV trips and an increased demand for parking spaces. Moreover, AVs could increase VMT as they can operate autonomously without needing a driver [19].

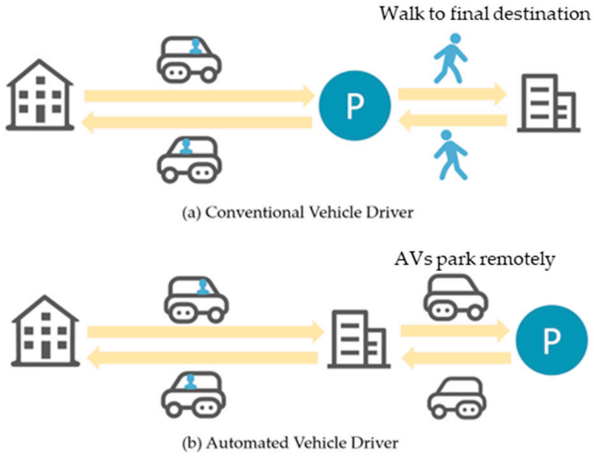

Figure 1. Parking pattern of automated and conventional vehicle drivers.

Understanding the potential environmental impacts of the growing adoption of AVs on urban parking is essential to address concerns surrounding traffic congestion, Greenhouse Gas (GHG) emissions, and air pollution [20]. By understanding the intersection of AVs and parking and exploring how AVs influence parking patterns, travel behavior, and parking facility energy efficiency, researchers can identify both the opportunities and challenges in terms of sustainable urban transportation. Proactive engagement in addressing these potential challenges is of paramount importance.

Few scholars have explored AVs' impact on parking [21] or analyzed the environmental influences related to AVs [19,22]. While some studies have forecasted the anticipated fluctuations in parking demand due to AVs deployment [23], others have delved into the environmental outcomes arising from these changes, encompassing factors such as traffic congestion and Pick-Up/Drop-Off (PUDO) scenarios [24]. The existing literature often positions automated vehicles as an emergent technology, discussing their ripple effects on travel modes or environmental outcomes [25–29]. Such discourses occasionally neglect AVs' potential as transformative transportation and their indirect repercussions on land use, urban spatial dynamics, and carbon emissions.

Hence, this study aims to investigate and map out the impact of AVs on parking demand and supply, along with their further environmental effects on land use and infrastructure, to guide toward better urban mobility system planning.

This paper is divided into five sections. Section 2 outlines the research method used in a systematic review. Section 3 employs bibliometric methods to examine the prevailing trends in the field of environmental impacts of AVs on parking. Section 4 presents the analysis results to answer the proposed five research questions derived from the systematic literature review. Finally, Section 5 discusses our findings and concludes this study with considerations for future research needs.

2. Methods

2.1. Definition of the Review Protocol

The first step entails defining the Research Questions (RQs) to delineate the scope of the literature review. In support of the study's aim to provide a comprehensive overview of the state-of-the-art knowledge on the environmental impacts of AVs on parking, the following research questions are proposed:

RQ 1: What are the different types of automated vehicles, and how do they impact parking demand and supply?

RQ 2: What are the potential effects of automated vehicles on the demand for parking and the associated environmental impacts (e.g., traffic congestion)?

RQ 3: What are the implications of automated vehicles on greenhouse gas emissions and air pollution from parking-related activities (e.g., idling, cruising for parking, PUDO)?

RQ 4: How do traditional parking facilities adapt to accommodate Automated Vehicles (AVs)?

RQ 5: What further research directions are recommended in the reviewed studies?

2.2. Data Collection

We arranged the study from three databases following the PRISMA [30] guidelines (Supplementary Materials): Web of Science, Science Direct, and Engineering Village. These publications are universally recognized within the academia for comprehensiveness and authoritative stature, which include engineering, transportation, mathematics, etc.

In pursuit of rigorous quality and precision, this study confines its scope to peer-reviewed journal articles with accessible full texts. The criteria for inclusion and exclusion, delineated in Table 1, govern the selection process. Each piece undergoes a meticulous review to ascertain its suitability for subsequent analysis. We conducted the last search in June 2023 and restricted all the literature extracted from those published before the date. The oldest paper was published in 2015.

Table 1. Criteria for inclusion and exclusion.

Inclusion Criteria	Exclusion Criteria
Written in English	Articles written in other languages
Research articles	Reviews, books or chapters, lecture notes, or encyclopedia
AVs/automated vehicles/autonomous vehicles/self-driving vehicles/driverless vehicles	Non-AVs

The search style and conditions of relevant databases are shown in Table 2. A total of 299 search results were obtained. After secondary screening and deduplication, 52 highly relevant articles from 123 authors were obtained [31–82]. The process of the literature selection is explained in Figure 2.

Table 2. Database query protocol executed.

Database	Search Terms Protocol	Additional Information
Web of Science	("Automated vehicles" OR "Autonomous vehicles" OR "Self-driving cars" OR "Driverless cars" OR "Connected and automated vehicles") AND ("Parking" OR "Parking facilities" OR "Parking management" OR "Parking strategies" OR "Parking infrastructure" OR "Parking demand")	-Search in the fields "Abstract" -Search in all publication dates -179 initial results
ScienceDirect	("Automated vehicles" OR "Autonomous vehicles" OR "Self-driving cars" OR "Driverless cars" OR "Connected and automated vehicles") AND ("Parking") AND ("impacts")	-Search in the fields "Title", "Abstract" or "Author-specified Keywords" -Search in all publication dates -56 initial results
Engineering Village	("Automated vehicles" OR "Autonomous vehicles" OR "Self-driving cars" OR" Driverless cars" OR "Connected and automated vehicles") AND ("Parking") AND ("impacts")	-Search in the field "Subject/Title/Abstract" -Search in all publication dates -64 initial results

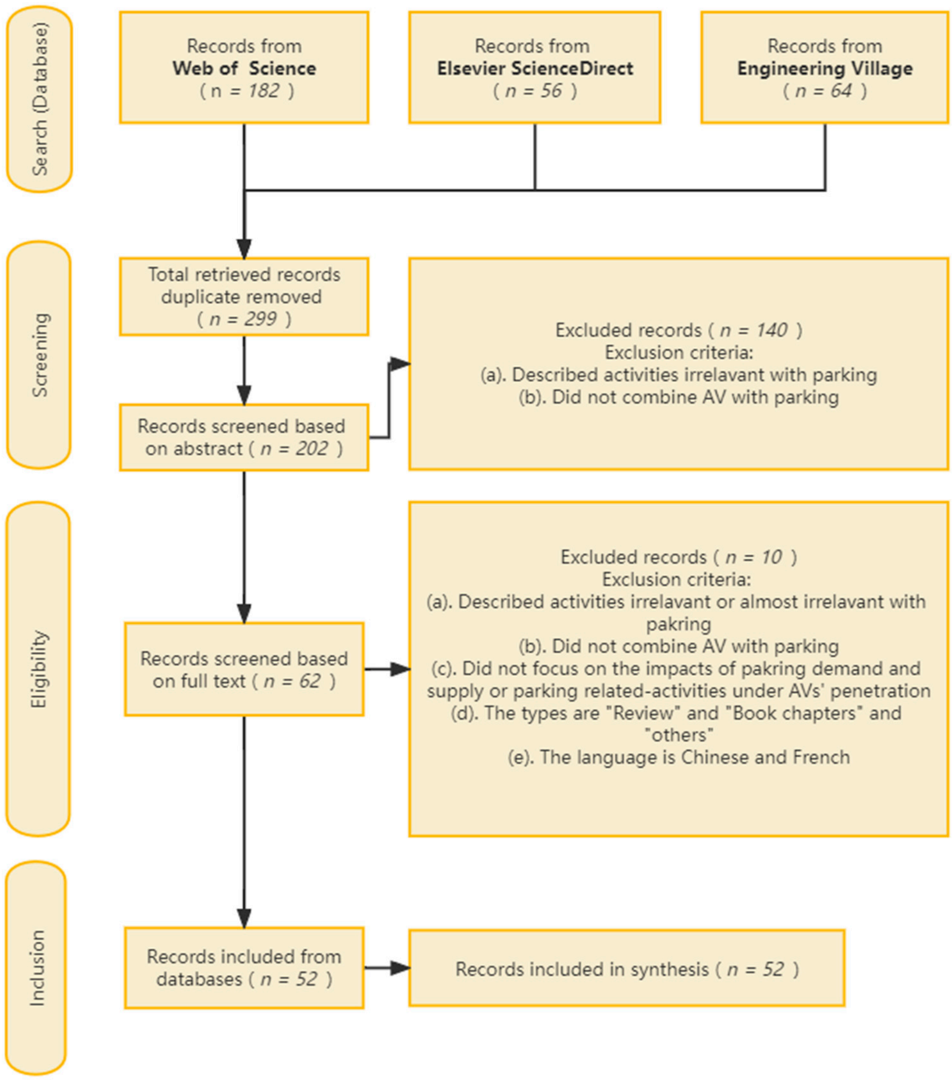

Figure 2. The flowchart of the literature selection process.

3. Analysis

This section employs bibliometric techniques to provide statistical analysis, encompassing the distribution of selected published papers, contributions by country, high-yield journals, prominent authors, highly cited papers, and keyword co-occurrence network.

3.1. Result Trends

As Figure 3 shows, from 2015 to 2023, the number of published articles related to the environmental impact of AVs on parking is on the rise. Between 2015 and 2016, the publication of relevant papers was relatively slow; Between 2016 and 2020, there has been a rapid growth in relevant papers. This trend might be attributed to the gradually maturing autonomous driving technology developed by established automakers (Mercedes Benz, BMW, etc.), and emerging startups like TuSimple in the US and Pony.ai, ZongMu Technology in China. The decrease in publication numbers may be due to the selection period considered only up to June 2023. It may have been influenced by the COVID-19 pandemic, as well as limitations in AVs' recognition capabilities under extreme weather conditions and possible ethical conflicts.

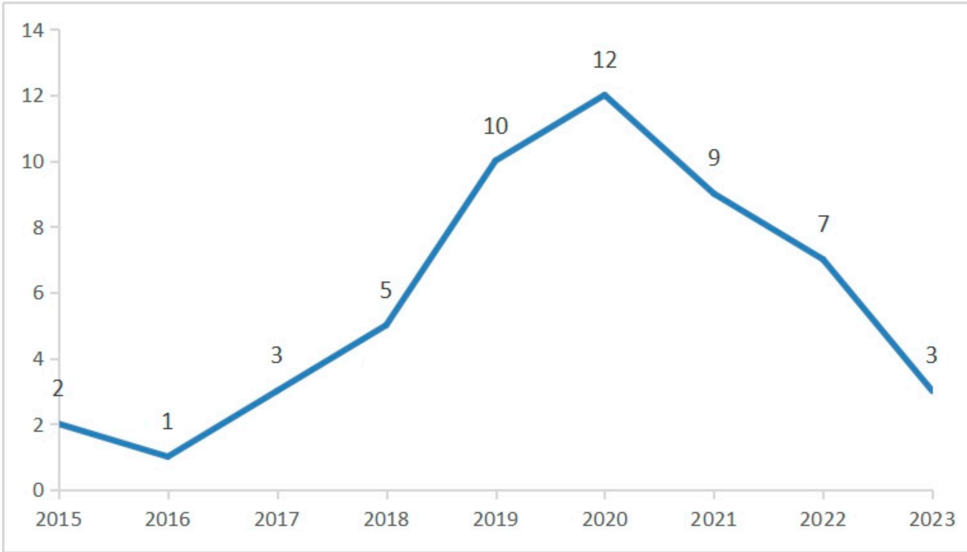

Figure 3. Number of relevant publications worldwide (2015 to June 2023).

3.2. Contributions by Country

Upon the systematic analysis of 52 manuscripts, investigations regarding the ramifications of AVs on parking were spearheaded by scholars across 18 nations. Figure 4 shows the spatial distribution of manuscripts from different nations. The United States emerged as the predominant contributor to this corpus, amassing 14 manuscripts, with China and the Netherlands trailing with six apiece. This pattern intimates a potential correlation between a country's research fervor and its foundational stature in this domain.

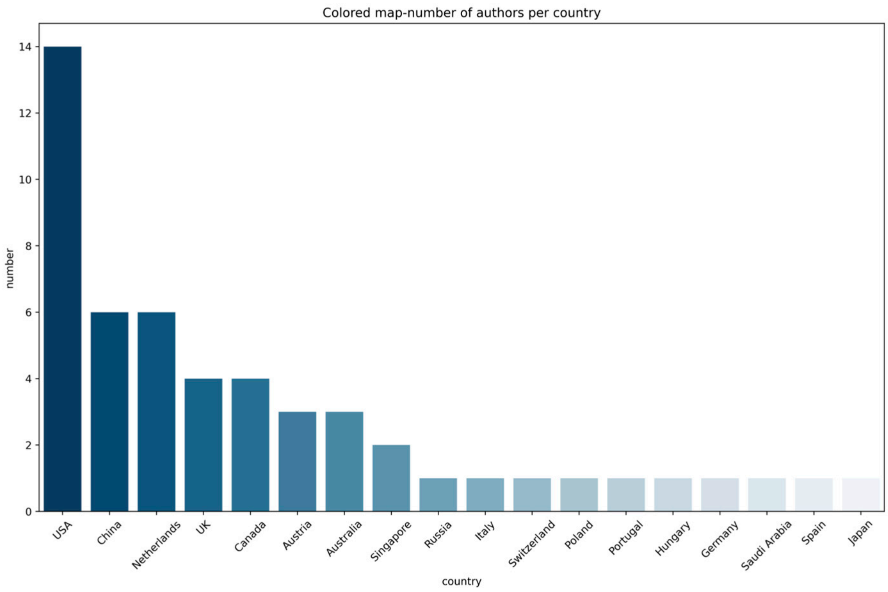

Figure 4. Spatial distribution of manuscripts emanating from various nations.

3.3. High-Yield Journals

The 52 articles under review were disseminated across 31 sources, of which six articles, or 11.5%, were published in the journal Transportation Research Part C—Emerging Technologies (as shown in Table 3). This concentration suggests that a significant portion of the studies were devoted to exploring the impacts of emerging AVs technology on changes in parking behaviors. Other significant sources of publication include Transportation Research

Part D, Transportation Research Procedia, and Transport Policy, each contributing 5.8% to the total.

Table 3. Number of journal publications (Top 6).

Journal	Number
Transportation Research Part C-Emerging Technologies	6
Transportation Research Part D-Transport and Environment	3
Transportation Research Procedia	3
Transport Policy	3
Land Use Policy	3
Cities	3

3.4. Highly-Yield Authors

Upon detailed analysis, it is observed that the 52 papers emanated from a collaborative effort of 123 authors. Table 4 enumerates the five foremost prolific authors and provides the citation counts for their respective works. Notably, among scholars investigating the environmental implications of AVs on parking, Bahrami, S., affiliated with the University of Michigan, United States, leads with an impressive five publications, amassing a total of 226 citations.

Table 4. Top 5 high-yield authors.

Author	Records	Citations
Bahrami, S.	5	226
Zhang, W. W.	4	673
Stead, D.	3	215
Roorda, M. J.	3	191
Levin, M. W.	3	60

3.5. Highly Cited Papers

Contrastingly, a prolific publication record for scholars does not inherently signify an elevated citation count. Manuscripts accruing the highest citation tallies have been isolated and delineated in Table 5. For instance, the manuscript by Zhang et al. in 2015 [31] has emerged as a recurrent citation in the domain, accumulating a formidable 447 references, underscoring its stature as a seminal work. Following closely, the work by Alessandrini et al. in 2015, detailing the prevailing status and trajectories of AVs, has garnered 367 citations.

Table 5. Top 10 most cited papers from the selected studies.

Authors	Citations	Paper Title
Zhang, W. et al. [33]	447	Exploring the impact of shared autonomous vehicles on urban parking demand: an agent-based simulation approach.
Alessandrini, A. et al. [72]	367	Automated vehicles and the rethinking of mobility and cities.
Soteropoulos, A. et al. [76]	356	Impacts of automated vehicles on travel behaviour and land use: an international review of modelling studies.
Zakharenko R. [60] Nourinejad, M. et al. [59]	222 185	Self-driving cars will change cities. Designing parking facilities for autonomous vehicles.
Zhang, W., Guhathakurta, S. [40]	169	Parking spaces in the age of shared autonomous vehicles: how much parking will we need and where?
Millard-Ball, A. [20]	160	The autonomous vehicle parking problem.
Dia, H., Javanshour, F. [73]	124	Autonomous shared mobility-on-demand: Melbourne pilot simulation study.
Maciejewski, M., Bischoff, J. [66]	117	Congestion effects of autonomous taxi fleets.
Stead, D., Vaddadi, B. [71]	93	Automated vehicles and how they may affect urban form: a review of recent scenario studies.

3.6. Keyword Co-Occurrence Network

In the analysis leveraging the co-occurrence function of VOSviewer, keywords from a plethora of articles were scrutinized, setting the minimum occurrence threshold at three. Figure 5 elucidates the primary research arenas, succinctly categorized into four distinctive clusters, each demarcated by a unique hue. The official VOSviewer documentation delineates a cluster as a collective set of items on a map, and items of analogous colorations belong to the same cluster. These clusters exhibit no overlap; a specific item is confined to a singular cluster. Upon examining the keyword map, terms such as "autonomous vehicles", "automated vehicles", and "parking" predominantly shaped the landscape. Notably, these terms were instrumental in orchestrating the article search.

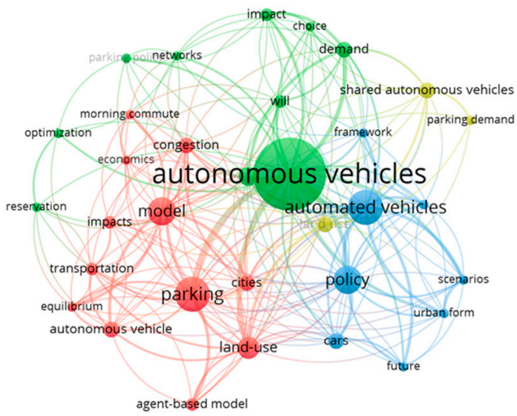

Figure 5. Keyword co-occurrence network. (land use in red, demand in yellow, policy in blue, impact in green, and models in red).

4. Results

4.1. RQ 1: Different Types of AVs' Impact on Parking Demand and Supply

4.1.1. Categories of Automated Vehicles

The most comprehensive system of standards in the automotive field is provided by the Society of Automotive Engineers (SAE). According to SAE, autonomous driving technology is categorized into six levels, from L0 to L5. L0 corresponds to conventional human driving without the inclusion of autonomous features, while Levels L1 to L5 represent progressive grades of technical configuration for autonomous driving. As indicated in Table 6, the literature referenced in this paper is classified according to the predominant level of automatic driving studied. Certain unclassified studies do not explicitly reflect the level of automatic driving under scrutiny. From the data, it is apparent that research regarding the impact of AVs on parking primarily concentrates on Level 4 and Level 5 automated vehicles (58%, 30 papers). A mere 6% (3) of the studies consider low-level vehicle automation, specifically Level 0 and Level 1.

Table 6. Levels of driving automation based on SAE.

Level	Name	Narrative Definition	Reference
0	No driving automation	The driver performs the entire Dynamic Driving Task (DDT), even when enhanced by active safety systems.	[37]
1	Driver assistance	A Driving Automation System (DAS) controls either the lateral or longitudinal vehicle motion subtask of the DDT, but not both simultaneously, expecting the driver to perform the remainder of the DDT.	[31,38]
2	Partial driving automation	A DAS controls both the lateral and longitudinal vehicle motion subtasks of the DDT, expecting the driver to complete the Object and Event Detection and Response (OEDR) tasks and supervise the DAS.	[31,38,39]

Table 6. *Cont.*

Level	Name	Narrative Definition	Reference
3	Conditional driving automation	An Automated Driving System (ADS) manages the whole DDT while expecting the user to be ready for fallback and to respond to system requests or failures.	[31,38,43]
4	High driving automation	An ADS performs the entire DDT and DDT fallback without any expectation for a user to respond to a request to intervene.	[31,34,38,41,43,48,49,55,57,60,61,63,64,67,68,70,75,78]
5	Full driving automation	An ADS performs the entire DDT and DDT fallback unconditionally (i.e., not operational design domain-specific) without any expectation for a user to respond to a request to intervene.	[36–39,41,47–49,52,55–58,60–64,66,68,70,73,75,77–79]

Furthermore, AVs can be categorized based on their ownership [36,40], type of operation [38], connectivity [32], power source [80], service provided [66,67], etc. For instance, Shared Automated Vehicles (SAVs) and Privately Owned Automated Vehicles (PAVs), these two types differ in their social attributes and operational characteristics, leading to variances in their parking requirements. SAVs are automated vehicles that are shared among multiple users. These could be part of a ride-hailing service (like Uber or Lyft) or a ridesharing service (like a carpooling service). Users can request SAVs to pick them up and drop them off at their final locations, and the SAVs drive directly to following passengers, the same as ATs. On the other hand, PAVs, due to their low occupancy, are often the key contributors to traffic congestion and parking demand in a region. Therefore, studying the changing dynamics of PAVs parking demand is highly valuable. Furthermore, the emergence of Electric Automated Vehicles (EAVs) also necessitates strategic planning for charging infrastructure [50,51].

4.1.2. Impact of Automated Vehicles on Parking Demand

Urban areas, particularly Central Business Districts (CBD), have limited space, which does not adapt easily to changing demands. The continued economic development has led to an influx of vehicles into cities, causing an imbalance between parking demand and available spaces. However, the rise of AVs presents a potential solution to this dilemma, as explained in Table 7.

Research suggests that PAVs could reduce the need for parking spaces, although they might not be as efficient as SAVs in this regard [57]. Contrarily, another study argued that PAVs might not significantly decrease parking demand because they scarcely influence vehicle utilization rates and ownership reductions [31].

The consensus among many studies is that SAVs will play a pivotal role in diminishing parking demand in cities. Sousa et al. concluded that on-demand services or shared AVs essentially eliminate the need for parking [46]. However, as parking costs escalate, SAVs may not necessarily lead to less congested urban roads. Millard-Ball's micro-simulation analysis indicates that SAVs might opt to cruise at slow speeds when constituting less than 15% of peak parking demand—rather than incurring parking costs [41,63]. A study using scenario construction showed that SAVs can remove all on-street parking and more than 80% off-street parking, but the demand for curbside loading and unloading may increase significantly [31]. Reference [63] argues that this cruising behavior necessitates the implementation of congestion pricing. Research data suggests that an SAVs system could reduce parking land by 4.5% in Atlanta, USA [40]. A study conducted in Budapest, Hungary, demonstrated that SAVs could cut parking demand by 33% to 83%, consequently reducing air pollution significantly [57]. In a simulation model by Zhang et al., integrating 700 SAVs could abolish up to 90% of the parking demand for the evaluated households [33]. The adoption rate of AVs is another crucial determinant; in Atlanta, a mere 5% market penetration could modestly decrease parking land [40]. Conversely, under a scenario with 100% SAVs coverage, parking demand could plunge by 94% compared to the present situation [77]. A dominant presence of SAVs might curtail the surplus vehicles triggered by the current travel demand. Incorporating ridesharing could further liberate urban land from parking constraints [76]. On academic campuses, as the SAVs fleet size escalates, parking spaces, potentially decreasing to under 2500 m^2, could be repurposed for academic endeavors [79].

Table 7. Impact of automated vehicles on parking demand.

Vehicle Type	Environmental Impact	Cases	Methods	Key Factors	Results	References
PAVs	Positive and negative	Atlanta, GA USA	Agent-based simulation model	AVs and shared mobility modes	Decreased off-street parking demand; increased mixed-use and residential parking demand	[31]
	Positive	Budapest, Hungary	Scenario building and urban space transformation model	People's acceptance of AVs	Scenarios featuring substantial shared AVs utilization indicate that parking demand could be reduced by nearly 83%	[57]
SAVs	Positive	Hypothetical 10 × 10 mi city	Agent-based simulation model	Vehicle fleet size	Up to 90% reduction in parking demand	[33]
	Positive	Singapore	Data-driven methodology	Total traveled kilometers increasing	Up to 90% reduction by people switching to SAVs	[35]
	Positive and negative	Atlanta, USA	Discrete Event Simulation (DES) framework and travel demand OD matrix	Parking cost	4.5% reduction in CBD parking demand; increased demand in low-income zones	[40]
	Positive	Budapest, Hungary	Scenario building and urban space transformation model	Fleet size, modal share, vehicle ownership, parking preference	33%–83% reduction in parking demand	[57]
	Positive	Seattle, USA and Grid network	Agent-based model	SAVs fleet size and AVs penetration rate	Parking lot shifts with 50% vehicle automation	[41]
	Positive	N/A	SWOT analysis	PUDO activity	Increased the use of on-demand services; reduced self-parking space	[46]
	Positive	Grid-based city	Travel demand, agent-based, and Activity-based model	SAVs fleet size and ridesharing size	Reduced parking spaces needed	[76]
	Positive	Okinawa, Japan	Dynamic traffic flow simulator	SAVs scenario and traffic flow	94.0% reduction in parking demand	[77]
	Positive	University of the West of England (UWE), Frenchay campus	DES model	SAVs fleet size	Increase in spaces released with SAVs fleet size	[79]
ATs	Positive	Berlin, Germany and Brandenburg area	Multi-agent transport simulation MATSim	ATs fleet size	Increasing SAV fleet size leads to more released parking spaces	[66]
	Positive	Austin, TX, USA	Life-cycle assessment framework	ATs fleet size	1.5% decrease in parking demand	[67]

AVs have the flexibility to cruise or park outside urban centers, thereby reducing the need for central city parking. However, PAVs and SAVs differ significantly in their capacity and methods for reducing parking demand [31,40,57]. While PAVs may initially gain widespread acceptance due to their enhanced privacy and comfort, SAVs are likely to gain traction as they increasingly meet these criteria [57]. The growing SAVs fleet size will notably lower urban parking demand, although an oversupply could lead people to switch from public transport, thereby increasing parking needs [57]. Overall, SAVs—given their propensity for constant movement—have the greatest potential for reducing parking demand, although unchecked growth could counteract these benefits.

Automated Taxis (ATs), which merge the concept of traditional taxis with automation, might also contribute to reduced parking needs. Traditional taxis, driven by humans, spend the majority of their time in transit or cruising for clients, thus minimizing parking requirements. Consequently, as AT fleets expand, not only will road capacity increase, but parking demand may decline [66]. A comparative study in Austin, TX, between conventional vehicles and a fleet of electric ATs revealed that the latter could slash GHG emissions by 60%, partly attributed to a 1.5% decline in parking [67].

4.1.3. Impact of Automated Vehicles on Parking Supply

To delineate the impact of AVs on parking supply as presented in Section 4.1.2 and differentiate it from the discourse on the impact of AVs on land use (analyzed in Section 4.2.1), our primary focus is on the spatial alterations in parking space requirements and the transformation of parking facilities (see Table 8).

Table 8. Impact of automated vehicles on parking supply.

Study (Author)	Vehicle Dimensions (l × w)	Layout/Design	Key Findings
[52]	Regular: 6 m × 2.5 m, AVs: 5 m × 2.5 m	Multirow layout	Traditional double-row max: 100 spaces. AVs era max: 255 spaces. Utilization: 99%.
[59]	Regular: 5 m × 2.8 m, AVs: 5 m × 2 m	Two-column design for lower demand; bigger islands with more columns for higher demand	AVs car parks reduce parking space needs by 62% on average, up to 87%.
[61]	2.64 m × 6 m	Addition of a PUDO zone	The optimal number of PUDO channels is two, yielding a net revenue of $405.24 over 8 hours.
[79]	4.8 m × 2.4 m	Not specified	10% SAVs implementation leads to a 12% increase in released land space.
[82]	Low-turnover: 2.64 m × 6 m, High-turnover: 2.74 m × 6 m	Double-row layout	Compared to "large" human parking spaces, efficiency gains range from 11% to 49%.

AVs have the potential to revolutionize the architecture and utilization of parking facilities in several compelling ways. Unlike traditional, human-driven vehicles, AVs can fit into narrower parking spaces. This is possible because these vehicles adhere to dynamic guidelines and safety norms, bolstered by advanced sensing and control systems. Research indicates that the dimensions required for parking could shrink by as much as 29% in the era of AVs [59].

Furthermore, AVs have the innate capability for self-organization, which allows for the creation of multirow parking layouts. This results in a considerable increase in parking space efficiency and utilization. For instance, Ye et al. have argued that while the maximum capacity of traditional double-row parking stands at 100 spaces, automated driving and parking could push this number to as many as 255 spaces. Such a configuration could achieve a staggering 99% utilization rate for a parking facility [52].

In addition, higher levels of automation systems can facilitate the physical separation of passenger PUDO zones from AVs storage areas. One study by Kong et al. exemplifies this through an analysis where a single facility features both a PUDO zone and vehicle storage. The study concluded that the optimal number of PUDO channels is two, and that this configuration can generate net revenues of $405.24 over an 8-hour period [61].

The impacts on parking are not confined solely to PAVs. SAVs also stand to dramatically reduce the need for parking spaces, particularly in CBDs. They also promise to cut down on the time and cost associated with finding parking. Research by Okeke et al. suggests that with just a 10% implementation of SAVs, the available space freed up could increase by approximately 12% [79].

4.2. RQ 2: The Potential Effects of AVs on the Demand for Parking and the Associated Environmental Impacts

4.2.1. Impact of Automated Vehicles on Land Use

As discussed in Section 4.1.2, most researchers hold the perspective that the implementation of AVs is anticipated to lessen parking demands, consequently decreasing parking space. Okeke [79] used the University of the West of England's French campus as a case study, revealing that an escalating SAVs fleet corresponded to a considerable liberation of land. Given the scarcity of land resources in cities, Kang et al. predicted a potential reclamation of 14.60% to 32.27% of the area presently allocated for parking, depending on the scenarios [75]. Furthermore, Bahrami and Roorda considered that prioritizing parking locations with minimal blockage probability could minimize the frequency of vehicle relocation [74].

Analyzing changes in urban land use is pivotal for crafting urban development strategies. Upon exploring the impact of AVs from a reverse perspective, the direct influence on urban morphology and spatial distribution was discernible [38]. However, making substantial modifications to existing parking facilities in the short term remains impractical. Consequently, urban planners might contemplate transforming static parking infrastructure into adaptable parking areas over time, accommodating the PUDO needs of shared mobility [32,35].

While the increasing prevalence of AVs can reduce transportation costs and expand available urban land, it may also boost energy consumption [34]. As we navigate the transition period of AVs, cities are expected to evolve, resulting in diversified land use in urban centers [43,49]. Hence, it is imperative to actively guide this development. One potential strategy involves implementing parking fees [40] and congestion charges [63]. In a many-to-one network setup, a combination of suitable CBD parking provisions and differentiated parking fees/subsidies could significantly alleviate queue congestion [56]. Nonetheless, the economics of parking lots, especially with charging, must be judiciously considered [65]. Harper et al. [41] demonstrated that a rising AVs penetration rate would increase VMT, significantly reducing parking lot revenue. Hence, implementing appropriate parking demand management policies is necessary. Wang et al. [55] devised a continuous time stochastic dynamic model to optimize parking management, helping determine the optimal pricing strategy for each parking lot. Another measure could be the provision of temporary parking, as proposed by Bruck and Soteropoulos [42]. Short-term parking near departure and destination points could mitigate the traffic congestion arising from AVs, utilizing street spaces or adjacent garages for temporary parking. (Table 9).

Table 9. Impact of automated vehicles on land use.

Title	Case	Key Factors	Results	Literature
Self-driving cars and the city: Effects on sprawl, energy consumption, and housing affordability	N/A	Reduced transportation costs and increased urban land availability	Decline in parking area requirement	[34]
Estimating savings in parking demand using shared vehicles for home work commuting	N/A	Shared mobility	Potential liberation of parking spaces	[35]
Parking futures: Preparing European cities for the advent of automated vehicles	N/A	Limitation of excessive AVs usage	Repurposing road and parking spaces for a greener city	[38]
Parking spaces in the age of shared autonomous vehicles: How much parking will we need and where?	Atlanta, USA	Penetration rate of SAVs	Approximately 4.5% reduction in parking land usage	[40]
Traffic land use compatibility and street design impacts of automated driving in Vienna, Austria	Vienna, Austria	Street space modifications	Enhancement in street livability	[42]
Spatial impact of automated driving in urban areas	Copenhagen metropolitan region	Usage of AVs	Duality of increased city sprawl and decreased road surface area	[49]
Designing parking facilities for autonomous vehicles	N/A	Redesign of parking facilities	A potential 62% reduction in parking space, reaching up to 87% in specific scenarios	[59]
Self-driving cars will change cities	N/A	Parking relocation	A decrease in the parking area at the cost of more empty travel	[60]
Assessing service characteristics of an automated transit on-demand service	Zurich, Switzerland	Cruising of vehicles	Potential to reduce public parking spaces, albeit with a minor surge in vehicle kilometers traveled	[69]
Automated vehicles and how they may affect urban form: a review of recent scenario studies	N/A	Adoption of AVs	Conversion of parking areas for alternative purposes	[71]
Automated vehicles and the rethinking of mobility and cities	N/A	Vehicle ownership	A reduction in space required for vehicle parking	[72]
Impact of automated vehicles on traffic assignment, mode split, and parking behavior	N/A	Cruising of vehicles	Scenario-based reduction in parking needs, ranging from 14.60% to 32.27%	[75]
The impacts of shared autonomous vehicles on car parking space	UWE Frenchay Campus	SAVs fleet size	Incremental release of parking spaces in tandem with SAVs fleet growth	[79]

4.2.2. Impact of Automated Vehicles on VMT

While there are significant uncertainties surrounding the anticipated impacts of AVs on VMT, prevailing research suggests a likely increase in VMT upon the integration of AVs. Such an increase is attributed to the advantages of faster and more comfortable journeys, as discussed by González-González et al. [65] and Alessandrini et al. [72]. Additionally, the lower per-kilometer travel costs associated with AVs may induce more frequent and extended trips [43].

Higher-level AVs could especially benefit underserved populations, such as the elderly and disabled, by offering safer and more convenient travel. This is likely to result in increased travel demand and, consequently, an escalation in VMT [39].

The adoption of AVs will have significant ramifications for the spatial distribution of both existing and future parking infrastructure. These shifts could exert either a positive or negative influence on VMT. For instance, there may be a shift in parking demand from CBDs and commercial zones to mixed-use and residential areas, which could, in turn, induce an increase in empty VMT [31]. Furthermore, the reduction in required parking spaces could result in an elevated number of empty circulating AVs, contributing to increased VMT [33,36,77].

Technological advances such as robust online business platforms and work-from-home software are reshaping work patterns. Consequently, there is the potential for a decrease in the demand for traditional workplace parking, with AVs expected to facilitate a 50% reduction in this demand while maintaining relatively low VMT [35]. Some research also suggests that while VMT may increase due to lower costs, a considerable reduction in public parking spaces could be observed [69]. PAVs owners could avoid parking fees and road tolls by opting to park at home or allowing their vehicles to cruise, thereby increasing empty VMT, fuel costs, and congestion [32,64]. Zhang et al. argue that cruising AVs will induce additional VMT [33]. Soteropoulos et al. [76] further posit that AVs may displace public transport, leading to increased VMT.

However, there exists a body of research that challenges the consensus on increased VMT due to AVs. For example, Bahrami and Roorda [54] conclude that when AVs operate without passengers, daily VMT decreases. According to Gawron et al., ATs have the potential to reduce GHG emissions by 60%, mainly attributable to the adoption of electrified powertrains. Up to 87% further reductions are achievable through electrical grid decarbonization, dynamic ridesharing, longer vehicle lifetimes, and accelerated improvements in fuel efficiency [67]. Concurrently, under specific scenarios like dynamic ridesharing, a reduction in VMT by up to 22% is plausible [67]. Levin et al. [58] suggest that while empty VMT could decline by approximately 18.5%, there may be a marginal increase in in-vehicle VMT. (Table 10).

Table 10. Impact of automated vehicles on VMT.

Causes	Environmental Impact	Methods	Cases	Key Factors	References
Faster travel	Negative	Pedestrian questionnaire survey	Adelaide CBD	Rise in total trips	[43]
	Negative	Think-tank model and target-oriented approach (initial stage)	N/A	Increased motorization and comfort	[65]
	Negative	Delphi survey	Multiple European cities	Increase in vehicular travel	[72]
Travel by underserved populations	Negative	Questionnaire survey	Adelaide CBD	Growing demand for AVs trips	[43]

Table 10. *Cont.*

Causes	Environmental Impact	Methods	Cases	Key Factors	References
Mode shift	Negative	Agent-based simulation	Atlanta Metropolitan	Relocation of parking	[31]
	Negative	Agent-based simulation	Hypothetical 10 × 10 mi grid city	Rise in empty vehicle cruising	[33]
	Negative	Data-driven approach	Singapore	Relocation of parking for home-work commuting	[35]
	Negative	Large-scale activity-based simulation	Amsterdam	Restricted parking facilities	[50]
	Positive	Agent-based simulation	Toronto	Toll for zero-occupant AVs	[54]
	Positive	Agent-based demand simulation	Melbourne, Australia	Distance-based pricing	[64]
	Negative	Life-cycle assessment framework	Austin, Texas	Empty kilometers caused by AT fleet	[67]
	Positive	Agent-based simulation	Zurich, Switzerland	Implementation of cordon charge	[69]
	Positive	System dynamics	N/A	Reduction in parking search time	[48]
Empty miles travel	Negative	P-median problem Lagrangian relaxation algorithm	New York City	Increased vehicle cruising	[32]
	Negative/ Positive	Stated preference survey	Seattle and Kansas City	Trip purpose, individual socio-economic and household characteristics, and local contexts	[36]
	Negative	Agent-based model	Seattle	Penetration rates of AVs	[41]
	Negative	Logit model	N/A	AVs empty repositioning	[58]
	Negative	SAVs dispatcher and SOUND dynamic traffic flow simulator	Okinawa, Japan	Expansion in SAVs fleet size	[77]

4.3. RQ 3: The Implications of AVs on GHG from Parking-Related Activities

Compared to conventional vehicles, AVs have the capability to evade parking fees by relocating to more distant parking lots or idling until the return of their passengers. Such behavior is poised to significantly alter parking-related activities, including idling, cruising for parking, and PUDO actions, which could subsequently affect GHG emissions.

Idling is associated with an increase in GHG emissions for both PAVs and SAVs. For PAVs, parking relocation results in increased empty VMT, thereby exacerbating GHG emissions, according to Reference [36]. Concurrently, idle SAVs, dispersed throughout the transport network, can significantly elevate the VKT without passengers, leading to an uptick in emissions.

The impact of AVs on GHG emissions from cruising for parking remains a topic of debate among researchers. Harper et al. [41] assert that a higher penetration rate of AVs will result in additional movements per day, particularly in Seattle. Conversely, Gawron et al. [67] and Shian Wang et al. [75] argue that AVs could reduce GHG emissions, mainly attributed to dynamic ridesharing, efficient energy systems, extended vehicle usage time, etc. A study in downtown Toronto [54] found that it was able to reduce VKT by 3.5% by charging zero-occupant AVs. The adjustment of parking costs in a specific area will also affect the repositioning behavior, thus affecting GHG emissions. The results of the Sioux Falls test network show that the adjusted parking cost can effectively reduce the congestion caused by the repositioning of empty vehicles, and reduce the emissions caused by the repositioning and congestion while optimizing parking [58].

Concerning PUDO activities, Larson and Zhao [34] contend that autonomous vehicles reduce commuters' need for parking and housing in urban centers, resulting in urban sprawl to the edge, which increases commuting time and congestion, potentially contributing to higher energy consumption and GHG emissions.

While AVs can cut GHG emissions due to enhanced electrification and energy efficiency, SAVs tend to offer more pronounced environmental advantages than PAVs [57,67]. SAVs generally have fewer idle cruises and can further minimize inefficient idle cruising through dynamic carpooling and operational efficiency, thus reducing transportation system emissions more effectively [67]. Infrastructure-wise, SAVs demand less parking than PAVs, allowing surplus areas to be repurposed as green spaces or charging stations, which can help mitigate related emissions [50]. Conversely, PAVs, with their inherent private nature, might prompt increased and longer travels, making their environmental benefits less significant than those of SAVs [36]. By implementing strategies such as charging for idle cruising, promoting dynamic ridesharing, and advancing energy systems, there is potential to promote better trip planning and further mitigate GHG emissions [54,58,69]. (Table 11).

Table 11. Impact of automated vehicles on GHG from parking-related activities.

Causes	Impact on GHG	Research Methods	Main Findings	Reference
Idling	Increase	Stated preference survey	Consideration needed for significant empty VMT from PAVs relocation	[36]
	Increase (56% and 42%)	System dynamics model	Potential car-km increase over 50% by 2050	[48]
	Increase	Large-scale activity-based simulation	The proposed parking management strategy leads to evenly distributed ATs in the network.	[50]
Cruising for Parking	Increase (2.5% and 2.1% at 100% AVs penetration rate)	Agent-based simulation	AVs (5–25% penetration) travel an extra 5.6–6.4 km/day on average	[41]
	Reduce	Agent-based simulation	A toll for zero-occupant AVs leads to the vehicle kilometers traveled decreasing by 3.5% in downtown Toronto.	[54]
	Reduce	Modified static traffic assignment and logit model	Adjusted parking costs effectively diminish congestion caused by vacant vehicle repositioning.	[58]
	Reduce	Life-cycle assessment framework	A 60% reduction in cumulative energy and GHG emissions by electrified AT fleet, up to 87% gained by dynamic ridesharing, efficient energy systems, extended vehicle usage time, etc.	[67]
	Increase	Optimization model	Scenarios with AVs can lead to approximately a 50% increment in average travel time.	[75]
PUDO Activity	Increase	Canonical mono-centric city model rendition	Urban sprawl and longer commutes	[34]

4.4. RQ 4: Conversion of Traditional Parking Facilities to Accommodate AVs

AVs are poised to bring substantial changes to current parking facilities in terms of form, location, and quantity. Among the existing literature, 12 articles particularly concentrate on these transformations, addressing aspects such as parking lot layout, charging infrastructure for electric vehicles, and the repurposing of parking lots for alternative uses.

References [52,61,71,82] illustrate that parking lots will likely be reconfigured with narrower spaces and multirow layouts to achieve a more space-efficient and intensive parking arrangement. In the case of EAVs, the strategic placement of charging stations becomes a crucial consideration [80,81]. Reference [80] proffers a heuristic approach grounded in genetic algorithms to address the system design of station locations and vehicle deployment. Further, as references [33,35], and others suggest, the need for parking facilities in city centers may diminish, as AVs could self-relocate to more affordable parking areas elsewhere in the city [38,43]. The liberated urban space might then be repurposed for public amenities, including high-quality green spaces, sports facilities, or cultural venues [72,79].

4.5. RQ 5: Further Research Directions Recommended in the Reviewed Studies

While several studies have neglected to propose future research directions, others have indicated prospective work or studies in progress. Often, these involve minor incremental modifications, such as changes to parameters, introduction of new inputs, or development of distinct scenarios. However, these specific studies are not addressed in this subsection, as their unique aspects would necessitate a substantial background understanding of the content, which is beyond the scope of this systematic literature review.

Vehicle automation technologies remain in a developmental stage and are characterized by their immaturity. Consequently, studies that relate to the uncertainties of future technological directions propose numerous areas for future research. However, due to space constraints, only a few typical examples will be discussed herein. Reference [31] highlights the ongoing uncertainty regarding public acceptance and the technological advancements of AVs. In a fully AVs-enabled environment, reference [41] posits that many cars are likely to be both autonomous and electric, thus substantially reducing energy consumption, emissions, and operational costs associated with driving (including fuel and maintenance). Considering SAVs as a distinct form of ridesharing, reference [76] suggests that matching algorithms could go beyond mere logistical considerations, integrating a social-emotional component to match passengers with similar social and emotional characteristics, thereby enhancing the ridesharing experience. Furthermore, references [46,52,56,75] explore the transformation process required for the emergence of AVs, indicating a likely prolonged coexistence between traditional and AVs. Lastly, reference [66] calls for additional research into the integration of AVs with public transport. The authors argue that combining public transport with ATs for last-mile trips may be a viable approach when ATs demand is low.

Some studies related to future work focus on policy aspects, including parking policy, parking management strategy, and congestion pricing schemes. Regarding parking policy, reference [38] calls for further research to validate and identify potential policy measures through specific case studies, comparing ideal driverless cities worldwide while considering different policy procedures, measures, and levels of acceptability. In the context of parking management strategies, reference [50] proposes future research to analyze the impacts of various parking management approaches. Finally, reference [64] highlights the current study's limitation regarding the omission of traffic congestion discussion. The authors argue that if congestion is to be addressed through tolls, such tolls should only apply to AVs loaded with passengers. Conversely, empty AVs, optimizing parking locations, should travel without charge. This rationale stems from the observation that empty AVs typically travel in the opposite direction of peak travel [60]. Thus, charging them would promote more centralized parking.

The studies about the proposed model (12 of 16) basically suggest more work needs to be conducted in adjusting the model with travel/parking demand changes or long-term land use variations. Reference [67] suggests that travel demand varies due to the lower cost of travel promised by ATs fleets or consumers' tendency to reduce travel, while in their study, travel demand was defined to be constant during the 30 years scenario. Complementing this, reference [77] underscores the need for more research into decision-making related to repurposing land use for socially favorable objectives, such as spaces dedicated to non-motorized modes of transport. (Table 12).

Table 12. Reported future studies.

Category	Segment	Reference
Technology	Electric AVs	[31,32,34,41]
	Shared AVs	[35,54,55,57,66,76,78]
	Integrate AVs with traditional traffic	[46,52,56,75]
	Combining emergent sources of data (MAAS, ride-share apps)	[44]
	Automation of public transport	[48]
Policy	Parking policy	[31,38,39,54,65,68]
	Parking management strategy	[50,51]
	Congestion pricing scheme	[51,54,60,62,64]
Model	Simulation of real road networks	[34,41]
	Changes in travel demand	[31,40,41,46,47,52,67]
	Land use	[31,39,42,45,47,76,77]
	Changes in transportation mode choices	[35,73]

5. Conclusions

While the future of AVs remains uncertain in many aspects, the findings of this study point out that the type of AVs plays a critical role in determining its impact on parking demand. For instance, SAVs and ATs are poised to substantially reduce the demand for parking in urban centers. In contrast, PAVs may not lead to a significant reduction in parking demand because of limited influence on vehicle utilization rates and ownership. Advancements in sensing and control systems in AVs are also expected to revolutionize parking supply. These technologies enable increased parking space efficiency through compact multirow parking layouts. Moreover, higher levels of automation can segregate passenger PUDO from AVs storage locations. While PAVs have specific implications for parking, SAVs can dramatically decrease the need for parking, especially in CBD. Although the anticipated impact of AVs on VMT is still uncertain, prevailing research suggests a potential increase due to the enhanced travel experience they offer. Lower per-mile travel costs may also encourage more frequent and extended trips.

In addition, AVs have the ability to minimize parking costs by relocating to distant parking lots or idling until passengers return. Such activities could profoundly influence parking behavior and affect GHG emissions. While idling increases GHG emissions, the impact of AVs on emissions from cruising for parking remains contested. Additionally, empty trips to CBDs for passenger pick-up could result in increased energy consumption. Meanwhile, the advent of Electric Automated Vehicles necessitates careful planning for charging station locations. The demand for centralized parking facilities may decline as AVs could relocate to more economical locations. Consequently, this liberates valuable urban spaces that could be repurposed for public amenities such as green spaces, sports complexes, or cultural centers.

The current state of research indicates gaps that warrant further investigation. While vehicle automation technologies are still evolving, a transitional period is anticipated where traditional and automated vehicles will coexist. Policy considerations, including parking management and congestion pricing schemes, also need to be evaluated. Existing models primarily suggest the need for adjustments to accommodate shifts in travel and parking demand as well as long-term land use changes.

Additional VMT from factors such as increased speed, mode shifts, and empty repositioning poses potential drawbacks to AVs adoption. However, optimized SAVs fleet sizes, smoother traffic flow, fewer cold starts, and dynamic ridesharing could mitigate some negative environmental impacts. To maximize the sustainable and equitable benefits of AVs, it is imperative for public and governmental stakeholders to regulate PAVs usage rigorously, formulate comprehensive urban and transportation policies, and investigate the advantages of emerging mobility and energy technologies.

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