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Synergizing Urban Mobility: The Interplay between Autonomous Vehicles and Autonomous Parking Spaces for Sustainable Development

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Abstract

Integrating autonomous vehicles (AVs) and autonomous parking spaces (APS) marks a transformative development in urban mobility and sustainability. This paper reflects on these technologies' historical evolution, current interdependence, and future potential through the lens of environmental, social, and economic sustainability. Historically, parking systems evolved from manual designs to automated processes yet remained focused on convenience rather than sustainability. Presently, advancements in smart infrastructure and vehicle-to-infrastructure (V2I) communication have enabled AVs and APS to operate as a cohesive system, optimizing space, energy, and transportation efficiency. Looking ahead, the seamless integration of AVs and APS into broader smart city ecosystems promises to redefine urban landscapes by repurposing traditional parking infrastructure into multifunctional spaces and supporting renewable energy initiatives. These technologies align with global sustainability goals by mitigating emissions, reducing urban sprawl, and fostering adaptive land uses. This reflection highlights the need for collaborative efforts among stakeholders to address regulatory and technological challenges, ensuring the equitable and efficient deployment of AVs and APS for smarter, greener cities.

Keywords

Autonomous Vehicles, Autonomous Parking Spaces, Sustainability, Smart Infrastructure

1. Introduction

The transition to autonomous vehicles (AVs) and the corresponding rise of autonomous parking spaces (APS) represents a pivotal opportunity to address sustainability challenges in urban and transportation systems. Historically, the environmental impact of conventional vehicles and traditional parking infrastructure has significantly contributed to greenhouse gas emissions, inefficient land use, and urban sprawl [1] [2]. Autonomous vehicles and intelligent parking systems can mitigate these issues by optimizing transportation networks and reducing wasteful practices.

The relationship between AVs and APS has emerged as a crucial area of focus in the quest for sustainable urban mobility. While autonomous vehicles are lauded for improving fuel efficiency and reducing traffic congestion, their sustainability potential is amplified when paired with autonomous parking spaces [3] [4]. Thus, by eliminating human intervention, APS can maximize land use efficiency, lower energy consumption, and integrate seamlessly with renewable energy systems. These synergies align with broader sustainability goals, such as reducing carbon footprints and creating resilient, livable urban environments. Nevertheless, the potential of these technologies to optimize urban mobility, reduce ecological footprints, and align with global sustainability objectives remains largely unexplored.

Accordingly, this reflection explores the historical, present, and future dimensions of the relationship between autonomous vehicles and autonomous parking spaces through the lens of sustainability. It examines how integrating these technologies can address critical environmental, social, and economic challenges while highlighting the steps needed to harness their potential fully. By examining the historical evolution of parking systems, the current technological interplay between AVs and APS, and their future prospects, this reflection emphasizes these technologies' transformative potential to optimize land use, reduce greenhouse gas emissions, and support renewable energy initiatives. The significance of advanced communication systems, smart infrastructure, and implications in promoting equitable and efficient deployment is also emphasized. This reflection is a critical resource for stakeholders striving to align technological innovation with global sustainability objectives and urban development requirements.

The remaining sections include the historical content in section two, the present relationship between the AVs and APS in section three, the future perspective in section four, reflection and implications in section five, and the conclusion in section six.

2. Historical Context

The relationship between parking systems and vehicles has evolved significantly over time, shaped by technological advancements and societal needs. In the early 20th century, the proliferation of personal vehicles prompted the creation of parking facilities such as street-side parking and standalone garages [5] [6]. These spaces were designed primarily for human-operated vehicles, emphasizing accessibility and manual control. The environmental impact of these facilities was rarely considered, as urban planners focused on accommodating increasing vehicle ownership rather than sustainability.

The mid-20th century marked the introduction of innovations aimed at improving parking efficiency. Parking meters, first implemented in Oklahoma City in 1935, were an early example of automation designed to manage limited urban space and reduce congestion [7]. By the 1980s, automated ticketing systems and early robotic parking garages emerged, offering glimpses of how technology could streamline parking processes [8]. Despite these advancements, traditional parking systems relied heavily on human drivers, resulting in inefficiencies such as idling vehicles searching for spaces and sprawling lots consuming valuable urban land.

The concept of autonomous parking gained traction in the late 20th century as advancements in robotics and artificial intelligence hinted at the potential for fully automated systems. Early prototypes of robotic valet parking systems, such as those deployed in Japan and Germany (see **Figure 1**), demonstrated the feasibility of reducing space requirements and improving parking efficiency [9] [10]. However, these systems were largely siloed, with limited vehicle interaction and parking infrastructure. Moreover, sustainability considerations remained peripheral, primarily focusing on convenience and cost reduction.

Japan's parking system in the 90s

Germany's parking system in the 90s

Figure 1. Parking systems in Japan and Germany in the 90s [11] [12].

The turn of the 21st century saw the emergence of smart technologies, including sensors, IoT devices, and data-driven systems, which laid the groundwork for modern autonomous parking spaces. These innovations coincided with growing concerns about the environmental impact of urban development and transportation systems. The recognition of parking's role in contributing to urban heat islands, emissions, and inefficient land use spurred interest in integrating sustainability into parking design [13]. Yet, the lack of widespread autonomous vehicle deployment limited the adoption of fully integrated autonomous parking solutions.

This historical trajectory highlights the gradual shift from manual and isolated parking systems to more automated and connected solutions. It also underscores the growing recognition of sustainability as a critical factor in transportation planning. The interplay between vehicles and parking has always been dynamic, but the advent of autonomous vehicles and parking spaces marks a turning point, offering new possibilities for sustainable urban mobility.

3. Present Relationship between AVs and APS

Today, the relationship between AVs and APS is characterized by increasing interdependence, driven by advancements in smart technologies, urban space constraints, and the push toward sustainability. The combination of these systems represents a shift in urban mobility, with AVs and APS complementing each other's functionalities to create a seamless and efficient transportation ecosystem. Autonomous vehicles with advanced technologies such as sensors, cameras, and artificial intelligence (AI) can navigate complex urban environments with minimal human intervention [14]. This capability extends to parking, where AVs can independently locate, access, and park in designated autonomous spaces. Modern APS is designed to support these advanced vehicles, incorporating features that streamline parking processes while addressing sustainability and urban efficiency challenges. Hence, **Figure 2** presents the feature integrations of the relationship between AV and APS.

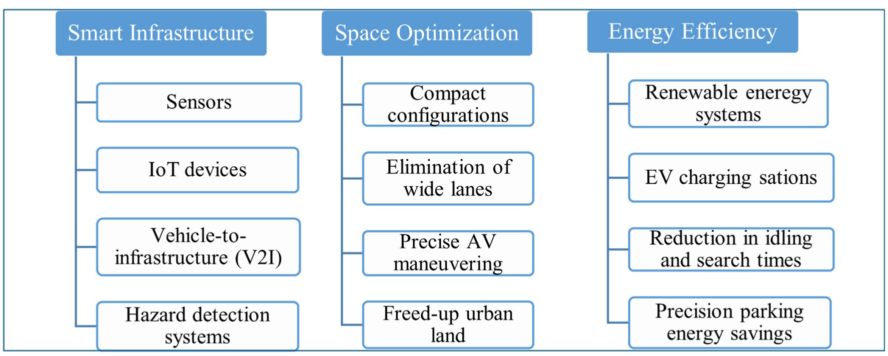

Figure 2. Features of AV-APS integration.

3.1. Smart Infrastructure

Modern APS has smart infrastructure, including sensors, IoT devices, and vehicle-to-infrastructure (V2I) communication systems. These technologies enable real-time interaction between AVs and parking facilities [15]. For example, sensors embedded in parking lots or garages can detect vacant spaces and transmit this information to nearby AVs, guiding them directly to the most efficient parking spot. This eliminates the need for vehicles to circle in search of parking, reducing fuel consumption and emissions. Integrating V2I technology improves efficiency and enhances the overall safety and reliability of the parking process. By communicating directly with APS, AVs can avoid potential hazards such as obstructions or misaligned spaces, ensuring a smoother parking experience.

3.2. Space Optimization

Traditional parking facilities are designed with human drivers in mind, requiring wide aisles, maneuvering space, and pedestrian access. In contrast, APS, which is designed for AVs, optimizes space utilization by eliminating these requirements. Since AVs do not require immediate proximity to human access points, such as building entrances or staircases, they can park in areas traditionally deemed less convenient [16]. Furthermore, AVs can drop passengers off at their destination and then autonomously park in remote or compact configurations, which reduces the need for wide driving lanes, pedestrian access pathways, and standard clearance for human maneuverability. Additionally, AVs can perform precise movements, enabling parking in compact or unconventional spaces that would be difficult for human drivers. This optimization improves efficiency and frees up urban land for alternative uses, such as green spaces, residential developments, or commercial areas, addressing the growing demand for sustainable urban planning.

3.3. Energy Efficiency

Energy efficiency is a critical component of the AV-APS relationship. Many APS facilities now integrate renewable energy systems, such as solar panels, to power their operations, aligning with global sustainability goals. Furthermore, APS often incorporates charging stations for electric vehicles (EVs), providing a dual function as parking and charging hubs. This integration supports the increasing adoption of EVs, many of which are also autonomous, creating a mutually beneficial cycle for clean energy and transportation [17]. Autonomous parking reduces energy waste associated with human-operated vehicles. Unlike traditional parking, where drivers idle while searching for spaces, AVs are guided directly to available spots, minimizing fuel consumption and emissions. Additionally, the precision of AVs in parking maneuvers reduces energy use during the parking process itself.

4. Future Prospects

The future relationship between AVs and APS holds immense potential to redefine urban mobility and sustainability. As AV and APS technologies mature, their integration will transform urban planning, environmental stewardship, and transportation. The future prospects of the relationship between Avs and APS would address how technological advancements, policy shifts, and societal adaptation could shape their dynamic relationship.

The future of AVs and APS lies in their seamless integration into broader smart city ecosystems. Advancements in vehicle-to-everything (V2X) communication will enable AVs to interact with APS and traffic management systems, public transportation, and emergency services. This interconnected infrastructure will optimize the flow of vehicles into and out of parking spaces, significantly reducing traffic congestion and emissions [18]. Dynamic pricing models could also become standard, powered by AI and real-time data. These systems would adjust parking fees based on demand, location, and environmental factors, incentivizing efficient parking behavior and maximizing operator revenue while encouraging sustainability.

As AVs drop passengers at their destinations and autonomously park in remote or less congested locations, urban spaces currently dominated by parking facilities will be repurposed for more productive uses. Large surface parking lots and multistory garages could be transformed into green spaces, residential complexes, or mixed-use developments, addressing critical urban issues such as housing shortages and public recreational areas [19]. This shift could significantly reduce urban sprawl and create a more compact, sustainable city design in cities where space is at a premium. Moreover, the ability to build parking structures in less desirable or underutilized areas will further alleviate the pressure on prime urban real estate.

Moreover, integrating renewable energy systems into APS is poised to become a standard feature in the future. APS facilities could serve as hubs for solar or wind energy generation, storing energy for use in operations and even feeding excess power back into the grid. Combining energy-efficient AVs and renewable-powered APS will align transportation systems with global sustainability goals, such as achieving net-zero emissions [20] [21]. Autonomous parking also supports transportation electrification. Future APS designs will likely incorporate advanced charging infrastructure capable of high-speed and wireless charging. As EV adoption increases, these facilities could play a central role in sustaining the energy needs of a fully electric vehicle fleet.

Future APS will likely adopt dynamic and multifunctional designs, allowing parking spaces to serve multiple purposes based on demand. For example, during off-peak hours, APS facilities could transition into delivery hubs for e-commerce, storage spaces for logistics, or staging areas for autonomous ride-sharing fleets. This flexibility will maximize the utility of parking spaces and contribute to a circular urban economy and sustainable freight transportation [19] [22]. Mobile or modular parking systems could also emerge, where portable APS units can be deployed in temporary or high-demand areas. These systems would provide adaptive solutions for events, seasonal peaks, or construction zones, adding a layer of resilience to urban infrastructure.

5. Reflection and Implication

The reflection and implication are done via a focus group of ten graduate students in the fields of transportation, urban planning and design, environmental science and sustainability, economic analysis and business innovation, and computer science. The discussions are transcribed and presented in the following paragraphs.

As the demand for human-centric parking spaces diminishes with the rise of AVs, a paradigm shift in land use becomes feasible. Thus, these systems collectively present a transformative opportunity to redefine how mobility and land use interact in urban environments, particularly in addressing the persistent challenges of resource inefficiency, emissions, and urban sprawl. The potential to repurpose surface lots and traditional parking garages into green spaces, mixed-use developments, or affordable housing projects aligns with broader goals of sustainable city development. This could address critical urban challenges like housing shortages and limited recreational areas while promoting compact, livable cities. Such transformations could also prioritize pedestrian and cyclist-friendly designs, further enhancing cities' social and environmental fabric.

From an environmental perspective, the implications of this technological convergence are equally significant. APS can mitigate carbon emissions and energy wastage by streamlining parking operations and reducing idling times. This reinforces the transition to low-carbon cities, particularly when APS facilities incorporate renewable energy systems and support the broader adoption of EAVs. Moreover, the data-driven nature of these systems opens the door to a more dynamic, sustainable energy ecosystem, wherein APS not only meets operational energy needs but contributes surplus power to the grid, fostering a decentralized and resilient energy model.

Economically, collaborating AVs and APS can potentially drive new business models and revenue streams. Dynamic pricing mechanisms powered by AI could optimize parking demand, while multifunctional APS designs could cater to various urban needs, such as serving as logistics hubs during off-peak hours. These innovations offer municipal authorities and private operators new opportunities to maximize the utility and profitability of parking infrastructures. Additionally, the widespread adoption of modular APS systems could address urban challenges with temporary, scalable solutions that adapt to shifting transportation demands.

Therefore, stakeholders, including urban planners, policymakers, technology developers, and environmental advocates, must coalesce to create regulatory frameworks and infrastructural investments that harmonize technological innovation with public interest. This approach ensures that the interplay between AVs and APS meets immediate operational goals and contributes to the long-term vision of sustainable, equitable urban mobility.

6. Conclusions

Integrating AVs and APS represents a pivotal shift in urban mobility and sustainability evolution. By enhancing land use efficiency, optimizing energy consumption, and incorporating renewable systems, the relationship between these technologies offers a comprehensive solution to critical urban challenges. Through seamless interaction enabled by advanced communication systems, AVs and APS can reduce traffic congestion, lower emissions, and transform traditional parking infrastructure into multifunctional assets, such as green spaces or mixed-use developments. This reflects a broader vision of more livable, sustainable, and resilient cities.

As this convergence continues, the success of AVs and APS will hinge on coordinated efforts across technology, policy, and planning. Stakeholders should address challenges such as regulatory frameworks, data privacy, and equitable access to ensure these innovations benefit diverse urban populations. Future developments in dynamic pricing, renewable energy integration, and adaptive parking solutions stipulate the potential of this collaboration to align with global sustainability goals. AVs and APS will redefine transportation efficiency and serve as a cornerstone for tomorrow's smart, interconnected cities.

The focus group's size and academic background may restrict the reflections' generalizability, as practical industry opinions and policymakers' perspectives were not directly included. Future studies should include broader stakeholder participation, such as urban officials, transportation sector professionals, and community leaders, to deepen the discussion. Additionally, empirical research is advised to verify the theoretical implications, with a particular emphasis on the economic and environmental consequences of integrating AV and APS in real-world scenarios. The social equity implications of these technologies, particularly their accessibility in marginalized communities, also warrant further investigation.

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Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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