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Implications of Autonomous Buses on Public Transit Systems: A Literature Review

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Abstract
In the age of rapid technological progress, the emergence of autonomous buses is reshaping public transportation. Powered by cutting-edge technologies, these buses signify a future marked by intelligent, secure, and eco-friendly urban mobility. This study employs VOSviewer for bibliometric analysis, focusing on the functional aspects of autonomous bus studies published between 2018 and 2024. The findings reveal that 58% of the studies originate from outside of Europe and the United States. The analysis highlights four key categories: Operational Efficiency, Safety and Compliance, Sustainability and Emission, and Passenger Experience. While cost reductions are expected, the feasibility of autonomous buses as a competitive option varies. Despite potential financial benefits from eliminating driver-related costs, concerns about user acceptance and safety advocate for personnel presence. This review highlights the need for further research in network design, vehicle resizing, and environmental impacts, offering insights into the complexities of integrating autonomous buses into public transit systems.

1. Introduction

In an era marked by technological advancement, the emergence of autonomous buses heralds a transformative shift in public transportation (Xie, 2022). Driven by cutting-edge technologies, these vehicles foreshadow a future where urban mobility transcends mere functionality, embracing intelligence, safety, and environmental consciousness. Against the backdrop of the transportation sector's substantial contribution to global CO_2 emissions, particularly from road transportation (Zhang et al. 2022; Zardini et al. 2022), the convergence of artificial intelligence, sensor arrays, and computational prowess positions autonomous buses as pioneers poised to revolutionize urban transit. Simultaneously, this urbanization trend is projected to persist, with the urban population set to grow 1.5 times, reaching 6 billion by 2045 and expected to more than double by 2050 (GMI, 2023).

The classification of autonomous vehicles by the US Department of Transportation, based on the SAE's definition, ranges from Level 0 (no automation) to Level 5 (full autonomy) (NHTSA, 2016, SAE, 2016). Within this spectrum, autonomous buses emerge as a natural progression in the quest for safer, more efficient, and eco-friendly transportation (Bösch, 2018, Litman, 2020). Historical roots trace back to experiments in robotics and vehicle automation, with autonomous guideway transit systems dating back to the late 1960s (Pastor, 1988, Gerland, 1980). Similarly, autonomous technologies such as driver assistance, collision warning and avoidance, precision docking, automatic lane-keeping, and lane-changing are being utilized in the transit industry, particularly on buses (Bishop, 2000, Chan, 2003).

The launch of the U.K.'s AB1 autonomous bus service in May 2023, part of the CAVForth project, marks a pivotal moment in public transportation. Operating on a 14-mile route in Scotland, this trial represents a groundbreaking step toward integrating autonomous vehicles, potentially revolutionizing future commuting patterns (Frangoul, 2023). While such advancements could enhance city bus systems, dynamic adjustments to capacity, trajectory, and schedules may be essential for broad acceptance (Nenseth et al. 2019; Cao & Ceder, 2019; Ma et al. 2020). These autonomous buses could either replace conventional public transport or complement it by adding new departures or providing first and last-mile transportation (Ainsalu et al. 2018; Bösch et al. 2018). A notable initiative involves the deployment of an autonomous shuttle service meticulously designed to meet the distinctive requirements of elderly individuals, thus offering a promising pathway toward enhancing urban mobility and fostering inclusivity (Kang et al. 2023). However, the initial low acceptance rate suggests a cautious approach, emphasizing the need for gradual deployment (Tian, 2022).

While acknowledging the potential negative societal implications, such as job displacement for bus drivers, in the scenario where autonomous buses entirely replace traditional ones, it is crucial to underscore the importance of standardized data acquisition procedures and comprehensive assessments of traveler choice behavior and service policies for effective optimization of bus networks (Shen et al. 2023). Despite the exploration of innovative mobility services by the private sector using autonomous vehicles to address congestion and emission issues in urban centers, there remains a significant gap in understanding the environmental and social sustainability of autonomous buses, especially when compared to traditional buses. This research aims to fill this void by conducting a systematic review focused on fully autonomous buses capable of operating without human drivers, recognizing the absence of a comprehensive literature review on the impact of autonomous buses on urban transit systems.

2. Materials and Methods

This paper delves into the intricate realm of autonomous buses, examining their technological foundations, societal consequences, ongoing challenges, and broader implications for the future of public transit systems, offering a thorough and insightful analysis of this emerging technology's potential impacts on urban transportation. This section describes the method used to compile and categorize the literature in this review. The types of publications considered for this review were primarily peer-reviewed journal articles and conference proceedings. The review of the impacts of autonomous buses (ABs) on the Transportation network and environment under the existing literature was carried out using the search engines Scopus and Google Scholar and Web of Science in April 2024. The first search included the most used keywords to refer to ABs, i.e., "Automated Bus," OR "Autonomous Bus" And "Minibus" OR "Shuttle" OR "Modular", yielding thousands of references.

Due to the rapidly evolving nature of the subject, our focus was limited to studies published in the English language from 2018 to 2024. This led to the inclusion of 118 articles that explored the impacts of ABs on both the transportation network and the environment. Following the initial selection, a comprehensive review was conducted to eliminate redundant and unrelated articles, resulting in the removal of 72 articles. We excluded studies focusing on Control System Design (sensor design, 5 studies) as we intended to specifically analyze the functional aspects within that context. After applying these criteria, we identified 46 articles using the "snowball" technique. Upon further examination, all 46 articles were deemed suitable for final inclusion in our study on autonomous vehicles (refer to Table 1). Subsequently, we presented a bibliometric analysis using VOSviewer to identify categories and keywords about the function of autonomous bus studies. Subsequently, we systematically review existing research and provide future recommendations regarding user attitudes and operational aspects. To conclude, we summarize the primary contributions, findings, and areas of further investigation within this study.

The bibliographic references were imported into VOSviewer for comprehensive bibliometric analysis. Renowned as one of the foremost tools in the field, VOSviewer is highly esteemed for its capacity to visualize and analyze bibliometric data (Shen, 2022). Through its visual network layout and sophisticated clustering algorithms, the program offers an intuitive representation of diverse relationships within the literature, such as co-authorship, co-citation, bibliographic coupling, and keyword co-occurrence. For further insights into the advanced algorithms utilized in VOSviewer readers can refer to Van Eck & Waltman (Van Eck, 2010)

3. Results and Discussion

At the initial stage, the classification process was initiated based on the examiner's studies and the titles under consideration. This categorization revealed distinct divisions, with the most prominent distinctions observed in the areas that have been extensively studied.

The database used for the analysis comprised the 46 papers obtained. To analyze the abstract of the paper, we set the minimum number of used keywords per article to four and one, respectively. These thresholds were established such that the analysis findings of VOSviewer would be straightforward and simple to comprehend and able to divide categories and keywords of the function of autonomous buses. An analysis of the findings regarding the relationships is shown in Fig. 1.

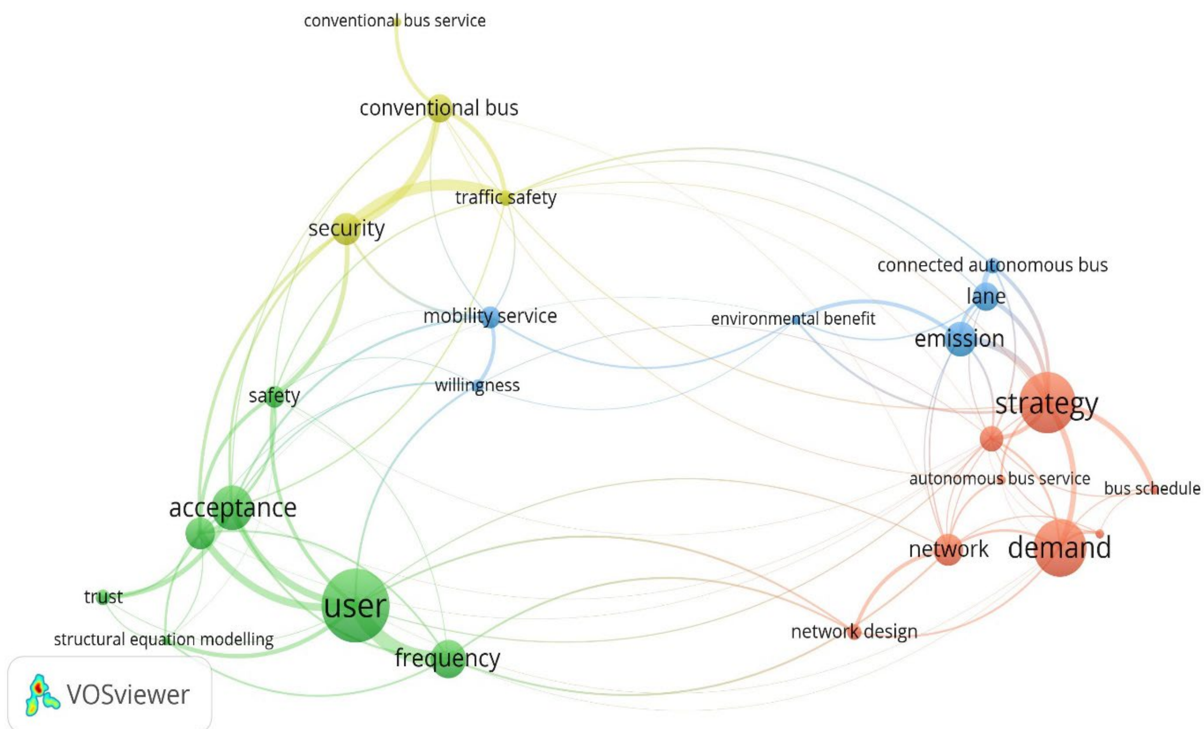

Figure 1. Relationships among various keywords in the abstract of the study

The categorization of autonomous buses can be divided into four distinct groups that emerged from the clustering of interconnected topics, drawing from their thematic resemblance and significance. These categories were formulated to establish a coherent framework for comprehending and addressing the pivotal facets of autonomous buses that are shown based on color in Figure 1.

In Figure 1, the size of each circle represents the frequency of occurrence of the corresponding keyword in the analyzed papers. Larger circles indicate keywords that appear more frequently and thus represent topics that have been studied more extensively. The color of each circle reflects its categorization within one of the four main thematic groups:

- Green: Passenger experience, including aspects such as user acceptance and survey results.
- Red: Operational efficiency, covering topics like demand, network design, and strategy.
- Yellow: Safety and compliance, addressing security and safety issues.
- Blue: Sustainability and emission, focusing on environmental benefits and emission-related topics.

The connections between circles represent the co-occurrence relationships among keywords, with thicker lines indicating stronger relationships. This visualization provides a clear overview of the research landscape and highlights the interconnected nature of topics within the autonomous bus domain. The number of studies relevant to each category and keyword is shown in Table 1.

Categories	Keywords	Sources Identified	Duplicates/off Topic	Selection by "Snowball" and relevance	Final Selection
Safety and Compliance	Lane Changing	118	72	1	1
	Dedicated Lane			1	1
	Safety and Security			1	1
Sustainability and Emission	Street Functional Classification & Trajectory			1	1
	Sustainability & Emission			3	3
Operational Efficiency	Traffic and Network			3	3
	Operation Cost			7	7
	Scheduling and Fleet Control			16	16
Passenger Experience	Policy and Social Acceptance			13	13

Table 1: Number of reviewed studies in each category

The results illustrate a concentration of studies on the impact of autonomous buses in two primary domains: Operational Efficiency and Passenger Experience (Figure 2). Furthermore, upon delving into the finer details of each category, a noticeable emphasis on Policy and Social Acceptance, as well as Scheduling and Fleet Control, becomes apparent. Both Policy and Social Acceptance, addressing legal, ethical, and societal considerations, and Scheduling and Fleet Control, optimizing operational efficiency and service quality within autonomous bus systems, stand out as pivotal aspects. Additionally, it is evident that the least studies focused on aspects such as operational costs, traffic management, and network integration to autonomous buses (Figure 3).

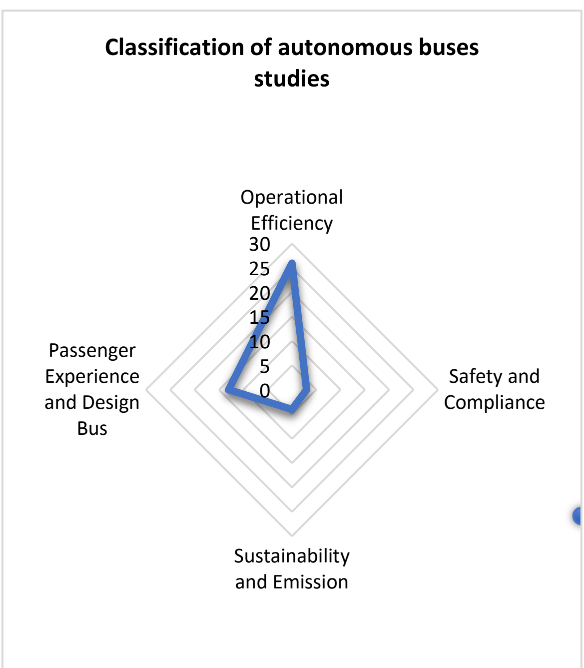

Figure 2: Number of reviewed studies based on classification of autonomous buses studies.

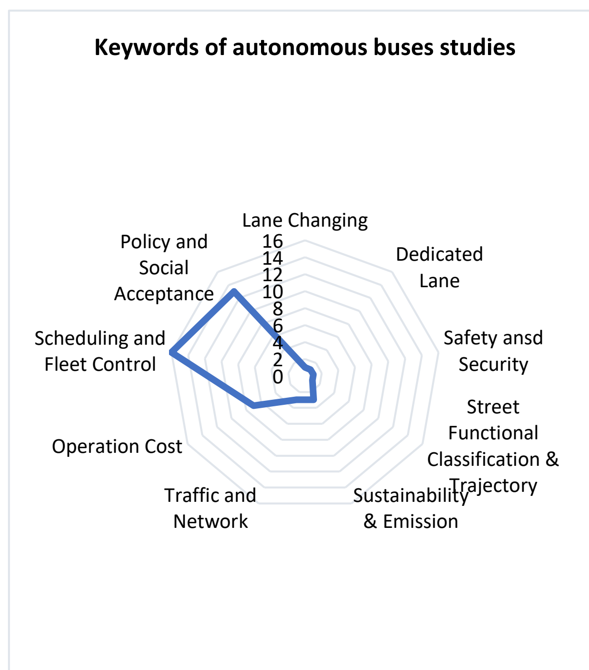

Figure 3: Number of reviewed studies based on keywords of autonomous bus studies.

In the following focusing on the function of fully autonomous buses, the discussion is structured around four key themes: Operational Efficiency, Safety and Compliance, Sustainability and Emission, and Passenger Experience. Each theme is accompanied by a summary table that captures essential aspects of each study related to the theme: (1) authors; (2) publication type; (3) study location; (4) methodologies; and (5) principal findings. The sources encompass a diverse range: journals, conference proceedings, reports, and book chapters. Geographically, the studies are categorized into the United States, Europe, and other regions. Methodologies employed encompass surveys, case studies, cost analyses, conceptual frameworks, position papers, simulation modeling, design approaches, interviews, risk assessments, expert opinions, and workshops. The key findings extracted from each study contribute to an aggregated analysis across studies, shedding light on potential research directions. These insights set the stage for subsequent sections, particularly addressing technological advancements.

3.1. Operational Efficiency

The category of Operational Efficiency Optimization encompasses the domains of Cost Operation, Scheduling & Fleet Control, and Traffic and Network. These domains were grouped as they all contribute to enhancing the operational efficiency of autonomous buses. The predominant methodologies adopted within this category varied based on the specific focus of each study. However, a common trend was the utilization of cost models and simulations.

Numerous studies have delved into the complex interplay between autonomous technology and traffic dynamics, operation costs, and network optimization within the domain of autonomous buses. Noteworthy investigations center on common objectives like optimized fleet management and resource allocation. Studies such as "Optimization of Bus Fleet Size and Mix" (Wang, 2021) and "Multi-Stage Optimization Model for Autonomous Bus Deployment" (Tian, 2022) emphasize the reduction of fleet size and the selection of optimal bus lines to lower operational expenses. These studies adopt optimization methodologies to address cost-efficiency challenges, considering both operational and economic factors. Furthermore, these studies address uncertainties in demand patterns, showcasing the need for adaptive strategies such as modular vehicle scheduling (Gao, 2023, Guo, 2024). Another study has the same result but shows that door-to-door services are more broadly applicable due to higher demand density thresholds (Badia, 2020). Moreover, it was found that an optimal fleet size of four shuttles can substitute a conventional bus route and reduce travel time through optimized vehicle movement (Xu, 2024).

Also, in the optimization process of the routes of buses, there are numerous uncertainties in the route planning and setting. In later studies, the uncertainty theory was introduced into the optimization problem of a customized bus route, and an uncertain customized bus route optimization model was established, which aims at minimizing the total mileage of vehicle operation. The results showed the system can fully satisfy the individual travel needs of passengers, but it is very challenging to efficiently operate (Tang, 2023, Sang, 2021).

In this landscape, cost considerations hold a pivotal role, as numerous studies delve into the potential financial benefits of adopting autonomous buses due to reduced driver expenses. Research indicates that integrating autonomous technology could lead to operational cost reductions of up to 50–60% (Bösch, 2018; Sinner, 2018; Cedera, 2018). However, discrepancies in methodologies and findings highlight the multifaceted nature of enhancing operational efficiency. While some studies suggest operational efficiency, gains ranging from 1.8% to 7% (Tian, 2021), Nagy's 2020 study reveals that implementing autonomous buses in a European city of 50,000 inhabitants could yield cost reductions of 17-24% compared to the current system (Nagy, 2020) and also Zhou's 2024 study in China shows the departure frequency was reduced by 22%, and the operating cost was reduced by 42% (Zhou, 2024). Conversely, another study demonstrates that increased service frequency raises service capacity and total cost due to higher operating expenses, offset by reduced user costs primarily attributed to shorter waiting times (Hatzenbühler, 2020).

"Romea, 2021," introduces an innovative breakthrough: Autonomous Driving Modular Buses equipped with adaptable units to elevate service speed and cost efficiency. This visionary concept heralds a transformative shift with the potential for substantial operational cost reductions. Studies like "Dynamic Dispatching of Semi-Autonomous Buses" (Dai, 2023) and "Operational Efficiency of Autonomous Bus Systems" (Muhammad, 2020) present diverse strategies, reflecting the intricate nature of efficiency enhancement. In a broader perspective, the collective findings of "Tian, 2022," "Ma, 2020," "Sinha, 2022," and "Wei, 2019" converge to create a holistic understanding of operational efficiency within autonomous buses. This synthesis centers on optimizing fleet management, elevating service quality, and effectively addressing challenges and strategic intricacies. While the potential for transformation is clearly present, skillfully navigating uncertainties and cost dynamics remains a vital factor for achieving a seamless integration.

In 2022, Sadrani's research emphasizes integrating automation and optimized services, yielding reduced user costs and a 24% increase in autonomous vehicle fleet service frequency. MA's 2020 study introduces a dynamic passenger-demand-responsive bus scheduling model within autonomous driving, enhancing efficiency and performance by addressing bunching, distribution, headway imbalance, and bus load. Modular vehicle scheduling and door-to-door services are identified as adaptive strategies. However, uncertainties in route planning present challenges in efficiently operating customized bus routes (Badia, 2020, Tang, 2023, Sang, 2021). Challenges persist, as Eikenbroek's 2020 work highlights uncertainty in autonomous travel times, advocating robust scheduling. underscores high initial autonomous vehicle costs, reduced operator costs, and emphasizes comprehensive cost-benefit analyses (Nagy's 2020, Hatzenbühler's, 2021). Zhai et al.'s 2020 autonomous bus-on-demand (ABoD) system showcases adaptability with optimized road allocation and responsiveness.

In conclusion, these studies collectively underscore the multifaceted nature of achieving operational efficiency in the context of autonomous buses. While minimizing operating costs, optimizing service quality, and reducing congestion are shared goals, addressing variations in strategies, challenges, and cost considerations is pivotal for the successful integration of autonomous buses into existing transportation systems. The studies also highlight the need to adapt to uncertain demand scenarios and dynamically optimize fleet size and assignments, showcasing the evolving nature of transportation solutions in the autonomous era (Table 2).

Author(s) (years)	**Type, Location**	**Methods**	**Key findings**
Bösch et al. 2018	Journal, Europe	Cost Analysis	The current form of public transportation will remain competitive only if demand is sufficient, e.g., in dense urban areas. Autonomous buses could be competitive in dense urban areas where the price of public transportation is lower than autonomous taxis
Sinner et al. 2018	Conference proceeding (TRB), Europe	Cost model (Zug, Switzerland)	Automation can affect transit network design parameters (such as accessibility, direct connections, and frequency), which would result in cost savings for the operator and the public sector. Automation can result in a savings of 50–60% of system-wide bus operating costs
Cedera et al. 2018	Conference proceeding (TRB), Europe and New Zealand	Simulation	Costs can be reduced by 20–64% if future systems are comprised of 75–100% autonomous public transport vehicles
Wei et al. 2019	Journal, Australian	Bus Operation Modeling, Cost Analysis	Compensatory crew cost reduction for fully autonomous buses offsets capital costs, but commercial speed obstacle needs addressing. Semi-autonomous bus benefits hinge on platooning feasibility and capacity, requiring network replanning and V2V communication.
Ma et al. 2020	Journal, China	Dynamic Optimization	Autonomous buses effectively alleviate bus bunching. Balance passenger distribution among buses Lower the degree of passenger flow and bus headway imbalance in the same section
Badia et al. 2020	Transportation Meeting, Spain	Cost Analysis	Door-to-door services are more cost-effective for transit stations feeding with autonomous buses due to a balanced cost distribution and operating cost reduction. Demand density threshold for competitive fixed routes is higher, but door-to-door services lead to longer user trip times due to internal routing and dispatching strategies.
Zhai et al. 2020	Journal, China	Agent-Based Modeling & Simulation.	Autonomous bus operating cost: $14.49 fixed + $0.45 marginal per seat per dispatch + $1.07 assembling/dissembling. Conventional human-driven bus operating cost: $39.18 fixed + $0.45 marginal per seat per dispatch.
Muhammad et al. 2020	Journal, China	Simulation Analysis	Introducing autonomous buses (AB) alongside autonomous cars (AC) improves traffic flow and road capacity due to carpooling potential and increased passenger accommodation in AB. Aggressive lane changes lead to notable growth in network flow rate and capacity, while polite lane changes have minimal impact.
Nagy et al. 2020	Conference Proceeding, Europe	Simulation and economic analysis	The study demonstrates potential savings achievable by implementing autonomous buses in a European city of 50,000 inhabitants, with projected cost reductions of 17-24% compared to the current system.

Author(s) (years)	**Type, Location**	**Methods**	**Key findings**
			Economic calculations reveal that while autonomous vehicle purchase costs are higher, operational cost savings are significant, potentially offsetting the higher upfront costs in around 5 years, leading to a more cost-effective system
Eikenbroek et al. 2020	International Conference, Europe	Robust Scheduling Technique and simulation	Autonomous bus operations maintain reasonable service regularity even in worst-case travel time scenarios.
Ma et al. 2020	Journal, China	Dynamic Dispatch Optimization and Simulation	For 50% AB penetration rate cases (i.e., 50% HB and 50% AB), passenger cost and total cost are decreased by 29% and 13%, respectively, at the sacrifice of increased bus operating cost by 26%. For all AB cases (i.e., 100% AB), passenger cost and total cost are decreased by 32% and 14%, respectively, with bus operating costs increased by 32%
Hatzenbühler, 2020	Journal, Sweden	Analytical Modeling and Simulation	increased service frequency raises service capacity and total cost due to higher operating cost, while user cost decreases, primarily due to reduced waiting time
Romea et al. 2021	Journal, Spain	Analytical modeling	While introducing autonomous modular buses can significantly decrease user and total costs, it might lead to higher agency costs due to increased pod requirements compared to current bus configurations.
Hatzenbühler. 2021	Journal, Sweden	Multi-objective Analysis and simulation	Results show increased service ridership, reduced operator cost, higher infrastructure cost, and more passengers taking the bus, with larger numbers walking to bus stops compared to conventional bus operations.
Wang et al. 2021	Journal, China	Agent-Based Modeling & simulator.	Simulation results demonstrate superior performance of the proposed algorithm over other reinforcement learning methods and scheduled bus systems, resulting in reduced fleet size and improved passenger wait times for less crowded routes.
Tian et al. 2021	Journal, Europe & Singapore	Optimization Model and Simulation	Numerical results highlight advantages of introducing autonomous buses, especially under significant demand uncertainty. Autonomous buses offer allocation flexibility, leading to reduced fleet size and total cost, even in the face of demand uncertainty.
Sang et al. 2021	Journal, China	Genetic Algorithm	Theory into bus route optimization effectively reduces total mileage from 35.6 kilometers to 32.2 kilometers. Utilization of an improved genetic algorithm validates feasibility and yields a reasonable customized bus route optimization scheme.
Tian et al. 2022	Journal, Europe & Singapore	Optimization Analysis	the importance of passenger adoption rates and highlight benefits of autonomous services, aiding decisions on deployment strategy
Sinha et al. 2022	Journal, Australia	Simulation Analysis	Connected autonomous buses (CABs) reduce travel time and standstill times, enhancing bus network performance.

Author(s) (years)	Type, Location	Methods	Key findings
			Potential conflicts between autonomous and manual vehicles indicated, with severity varying based on CAV penetration.
Sadrani et al. 2022	Journal, Germany & Chile	Mathematical Modeling & Simulation	User Cost Reduction: The inclusion of automation and optimized service results in reduced user costs due to improved service quality and reduced waiting and crowding discomfort. Service Frequency Increase: The article indicates that in the presence of on-board crowding effects, service frequency can increase by around 24% for autonomous vehicle fleet operations in some scenarios, leading to more frequent services.
Dai et al. 2023	Journal, China	Cost Analysis and Simulation	Simulation results demonstrate a significant reduction in bus operating cost (29.2%) and passenger waiting time cost (18.2%) compared to conventional human-driven bus scheduling.
Gao et al. 2023	Journal, China	Modular vehicle scheduling optimization.	Novel system optimally combines/separates modular units for balanced trip demands with EV constraints and charging plans. The proposed model decreases operating costs by approximately 25% compared to conventional electric buses, validated with real transit data
Tang et al. 2023	Journal, China	Optimization Model	Analysis of flexible electric buses and fixed-route transits integration optimize routes and timetabling plan for flexible bus. Spatial dispersion of demands The system can fully satisfy the individual travel needs of passengers. Combines the flexible buses with fixed-route transits.
Xu et al. 2024	Journal, Australia	Simulation	Replacing a traditional bus service line with connected shuttles Autonomous shuttles can reduce travel time because of optimized vehicle motion and fleet size (4 shuttle) Attractive appearance of this novel mobility mode may not necessarily enhance ridership
Guo et al. 2024	Journal, China	Optimization Model	Customized modular bus (CMB) systems that leverage travel demand prediction. The model can generate highly accurate predictions, with an average error of 1 passenger. Reduction of operating costs by up to 21% and highlights the role of module capacity and time dependency.
Zhou et al. 2024	Journal, China	Optimization Model	Approach was Minimize enterprise operation and passenger travel costs by considering speed regulation and capacity variation. the AB system effectively reduces the number of vacant seats and departure frequencies through speed regulation and capacity variation, thereby lowering operational costs. The departure frequency was reduced by 22%, and the operating cost was reduced by 42%

Table 2: Key studies on Operational Efficiency issues of autonomous buses

Operational Efficiency of autonomous buses involves various categories, such as Cost Operation, Scheduling & Fleet Control, and Traffic and Network. Common methodologies include cost models, optimization models, and simulations, while key objectives focus on optimizing fleet management, resource allocation, and reducing operational expenses. Financial benefits are anticipated, with potential cost reductions, but the findings vary. Emphasizes that the cost competitiveness of autonomous buses is not universal but dependent on specific scenarios. Autonomous buses can be more cost-competitive compared to other transportation options, such as autonomous taxis, in specific situations but increased travel time and spatial dispersion of demands in flexible buses. Innovative concepts like Autonomous Driving Modular Buses and Passenger-Demand-Responsive Scheduling aim to transform efficiency. Integration involves skillful management of uncertainties and cost dynamics (Figure 4).

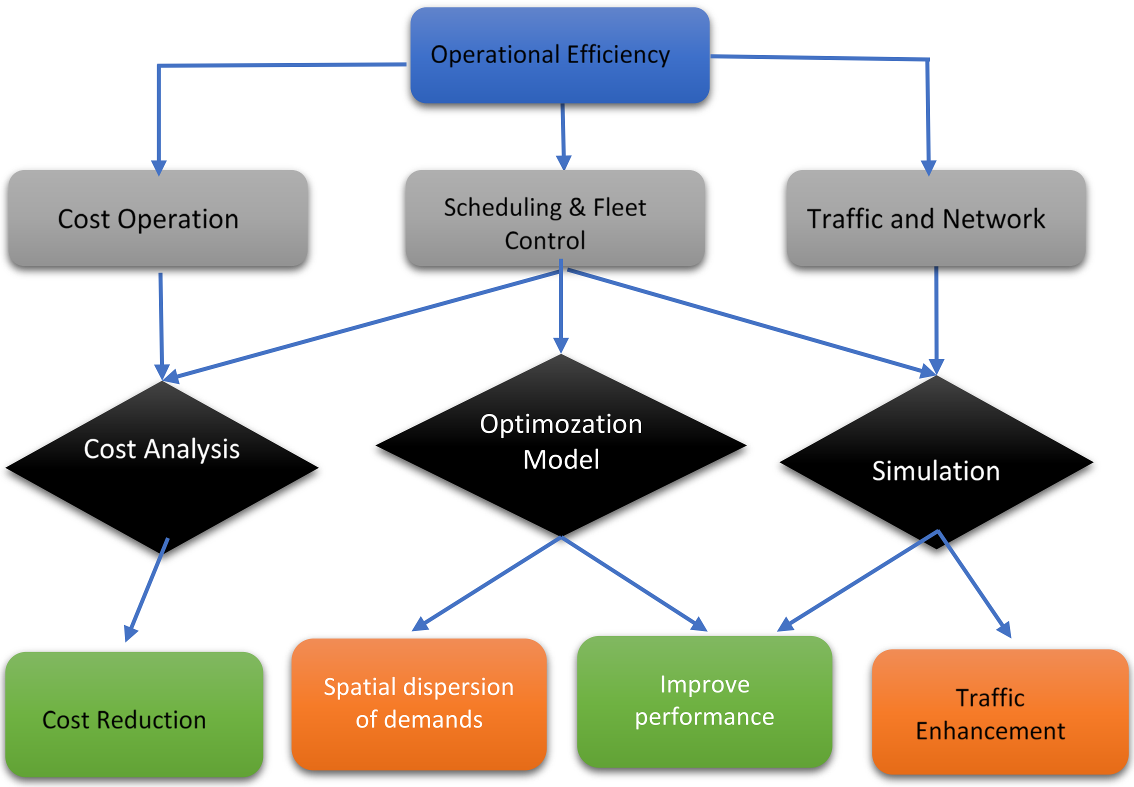

Figure 4. Key Findings of Autonomous Buses Based on Operational Efficiency

3.2. Safety and Compliance

The issues of Lane Changing, Dedicated Lane, and Safety were grouped under this category as they all pertain to ensuring the safety and compliance aspects of autonomous buses. This includes safe lane-changing maneuvers, dedicated lanes for improved safety, and implementing safety measures to prevent accidents. A summary of the most relevant studies is provided in Table 3.

The triad of studies focused on the safety of autonomous buses. These studies collectively delve into various dimensions of safety, ranging from passenger perceptions to behavioral dynamics and innovative infrastructural strategies. The focal point is to understand how autonomous buses can ensure the well-being of passengers while navigating a terrain that integrates both technological advancements and human concerns.

In the realm of autonomous buses, the amalgamation of research by Salonen (2018), Yao (2021), and Zhang (2022) has illuminated a comprehensive understanding of safety considerations. Salonen's exploration into passenger perceptions brings to light the paradoxical nature of feeling safer in driverless shuttles yet apprehensive about in-vehicle security. Yao's study on behavioral dynamics reveals the evolving interaction patterns between connected autonomous buses and human-driven counterparts, emphasizing their coexistence. Zhang's innovation underscores the proactive approach of dedicated CAB lanes to enhance safety and efficiency. Together, these studies offer a holistic perspective on the complex landscape of autonomous buses, encompassing passenger sentiments, vehicular behaviors, and innovative infrastructural adaptations.

Author(s) (years)	Type, Location	Methods	Key findings
Salonen et al. 2018	Journal, Finland	Survey	Survey respondents perceive traffic safety to be better in driverless shuttle buses than in conventional buses. 64 percent of respondents felt that driverless shuttle buses were worse than conventional buses in terms of in-vehicle security (probably due to a lack of drivers)
Yao et al. 2021	Journal, China	Lane Change Modeling, Simulation	Connected autonomous bus prefers lane changes for exiting. Hybrid human-driven buses show conservative lane-change tendencies.
Zhang et al. 2022	Journal, United States	a multimodal network equilibrium model	Use of a multimodal network equilibrium model and a mixed-integer nonlinear program to optimize autonomous buses (CAB) lane allocation, considering limited autonomous passenger vehicles access, leading to increased CAB ridership, improved overall system performance, and enhanced social benefits.

Table 3: Key studies on Operational Efficiency issues of autonomous buses

Research on safety and compliance for autonomous buses highlights passenger perceptions, behavioral dynamics, and innovative infrastructural strategies. Passengers may paradoxically feel both safer and apprehensive, emphasizing the importance of understanding their trust in driverless technology. The evolving interaction patterns between autonomous and human-driven vehicles underscore the need for safe coexistence on the road. Innovative infrastructural solutions like dedicated lanes aim to enhance safety and efficiency (Figure 5).

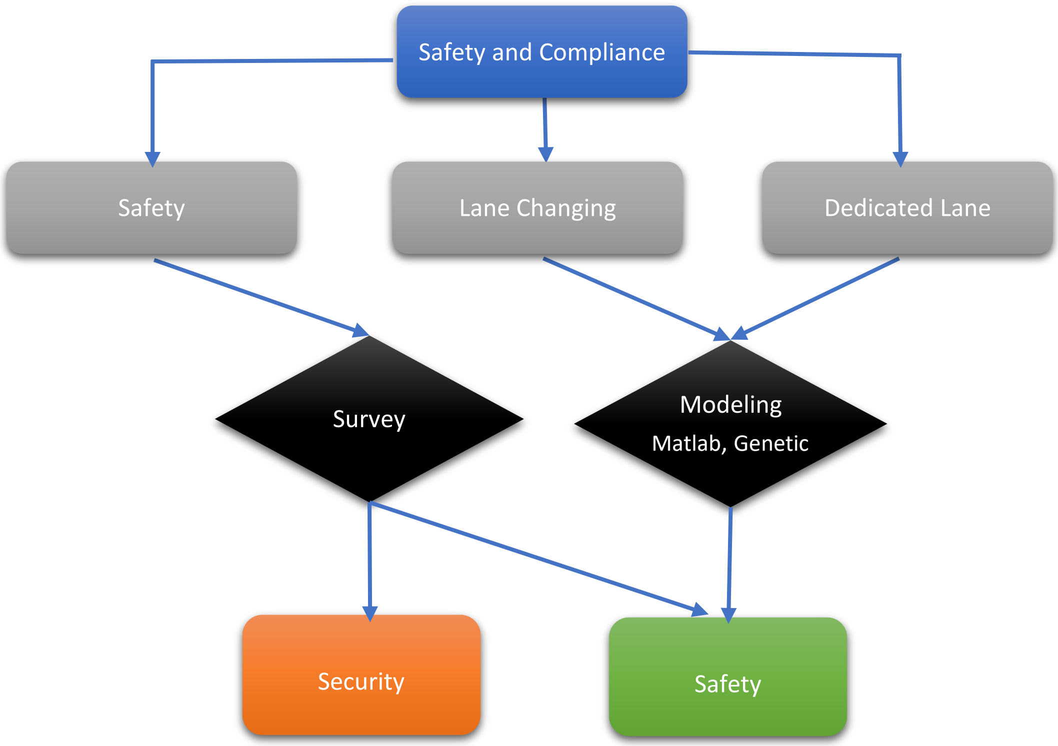

Figure 5. Key Findings of Autonomous Buses Based on Safety and Compliance

3.3. Sustainability and Emission

The issues of Sustainability and emission, Street Functional Classification, and Trajectory were grouped under this category as they all relate to sustainability and environmental considerations. This includes adopting sustainable technologies, considering street functional classification for optimal performance, and trajectory planning for efficient and eco-friendly operations (Table 4).

The study by Wang (2019) introduces a trajectory planning approach for connected and autonomous transit buses to enhance fuel efficiency, resulting in substantial reductions in bus energy consumption. In another study, Zhang (2020) investigates the environmental impact of autonomous buses, revealing reduced emissions and energy usage. The Singapore-based research evaluates autonomous electric minibuses, showing a significant 43% cost reduction and a remarkable 47% decrease in life-cycle greenhouse gas emissions compared to diesel buses, emphasizing their potential as a sustainable transportation solution (Pathak, 2021). The utilization of dedicated managed lanes further enhances these benefits, especially for bus emissions and energy consumption. This indicates the potential for autonomous buses to significantly mitigate the overall environmental impact of traffic flow in urban settings. In summary, these studies highlight the promising impact of connected and autonomous technologies on urban transportation efficiency, fuel consumption, and emissions reduction. The results offer a glimpse into the future potential of sustainable and transformative mobility solutions.

Martin (2021) introduces a new approach to autonomous bus parking, optimizing path planning by considering vehicle attributes and parking space availability. The algorithm successfully generates efficient parking trajectories in simulations, with a slight failure rate due to specific maneuver prerequisites. However, it cannot handle dynamic obstacles, suggesting a potential improvement by integrating real-time trajectory planning.

Author(s) (years)	Type, Location	Methods	Key findings
Wang et al. 2019	Journal, China	Real-time trajectory optimization, Mathematic model	the reduction in bus energy consumption by the proposed strategy is up to 27.8 and 16.4%, respectively, when compared with an aggressive strategy and an alternative strategy
Zhang et al. 2020	Journal, China	Simulation, Environmental Impact	Autonomous buses with CAV technology in Beijing reduce exhaust emissions and conserve energy. Managed lane strategy significantly lowers emissions and energy consumption of autonomous buses, showcasing potential benefits for urban expressway
Pathak et al. 2021	Journal, Singapore	Cost and emissions analysis.	Study in Singapore demonstrates a 43% reduction in total life-cycle cost for autonomous electric minibuses compared to 12-m diesel buses. 6-m autonomous electric minibuses exhibit a 47% decrease in life-cycle greenhouse gas emissions versus 12-m diesel buses, despite higher vehicle numbers
Martin et al. 2021	International Conference, Europe	Trajectory generation for parking	The algorithm provides efficient parking solutions for autonomous buses in various scenarios. 11% failure rate for perpendicular parking and 15% for parallel parking due to specific maneuver requirements not being met.

Table 4: Key studies on Sustainability and Emission issues of autonomous buses

Key findings in the context of sustainability and emissions for autonomous buses highlight the potential for enhanced fuel efficiency, reduced energy consumption, and lowered emissions through trajectory planning and the adoption of sustainable technologies. Studies demonstrate significant cost reductions and a remarkable decrease in greenhouse gas emissions with autonomous electric minibuses. Dedicated managed lanes further enhance these environmental benefits, pointing to the potential of autonomous buses to mitigate the environmental impact of urban traffic flow. Additionally, research introduces optimized path planning for autonomous bus parking, although it may benefit from improvements in handling dynamic obstacles in real-time scenarios (Figure 6).

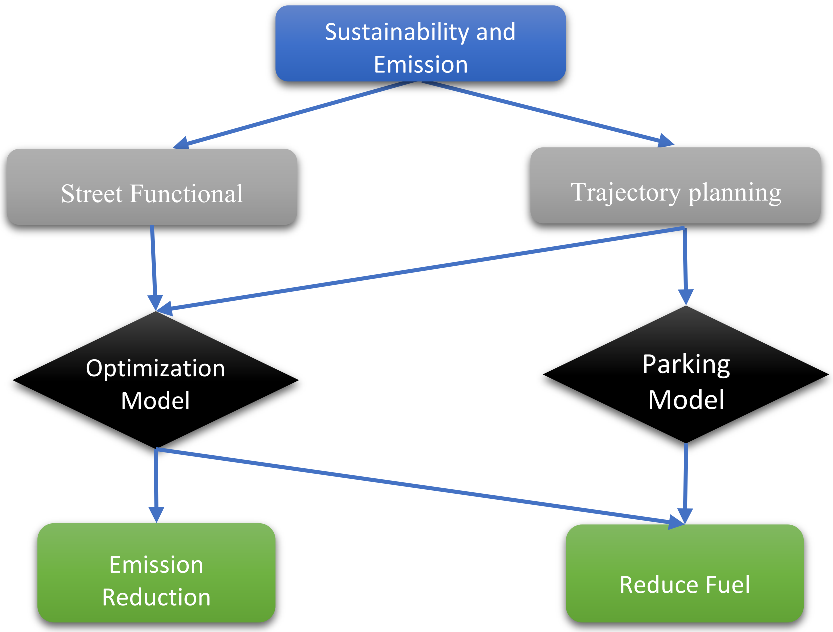

Figure 6. Key Findings of Autonomous Buses Based on Safety and Compliance

3.4. Passenger Experience and Design Bus

The issues of Policy and Social Acceptance, and Size and Control System Design were grouped under this category as they all focus on enhancing the passenger experience and designing user-friendly buses. This includes autonomous addressing policy and social acceptance factors, and designing buses with optimal size, control systems, and aesthetics that summarized in Table 5.

A collection of studies delving into the acceptance of autonomous buses provides a multifaceted understanding of this evolving transportation mode. Including compatibility, relative advantage, safety/security risks, perceived risks, in/out-of-vehicle time, and travel costs (Cheng, 2024)

Authored by Wintersberger (2018, 2022), Dong (2019), Xi (2020), Soe (2020), Chee (2020), Guo (2021), Zhao (2022), Chinen (2020), Wu (2021), and Mouratidis (2021), these research endeavors collectively underscore the role of comfort, safety, service quality, and convenience as pivotal factors influencing users' attitudes (Table 5).

The convergence of insights from Chinen (2020), Wu (2021), Wintersberger (2018, 2022), Xi (2020), and Mouratidis (2021) underscores the intricate and multi-dimensional nature of user acceptance and factors impacting autonomous bus adoption—encompassing positive perceptions of ease of use, addressing driving speed concerns, and catalyzing heightened intentions through enhanced service frequency and operational familiarity.

Studies by Guo (2020, 2021), Zhao (2022), and Mouratidis (2021), underscore the integral role of safety and trust in the acceptance and long-term adoption of autonomous buses. Guo's research indicates that passengers' perceptions of safety, reliability, driving speed, and convenience significantly impact their acceptance. Zhao's longitudinal study emphasizes evolving factors influencing experienced users' continued adoption, including perceived safety and comfort. Mouratidis' study reveals that passengers' real-world experiences with autonomous buses influence their intention to use such services, with user suggestions for enhancing speed and braking.

Author(s) (years)	Type, Location	Methods	Key findings
Wintersberger et al. 2018	International Conference, German	Survey	Participants questioned the utility of autonomous bus shuttles due to reduced speed
Dong et al. 2019	Journal, United State	Survey, logit modeling	many transit passengers will willingly board early generation autonomous buses
Soe et al. 2020	Journal, Estonia	Survey	passengers' perceived feeling of security and safety onboard was remarkably high
Xi et al. 2020	Journal, China	Survey, logistic regression model	Women are less willing to choose autonomous buses than men, and older people aged above 50 are more likely to use the mode
Chee et al. 2020	Journal, Sweden	Survey	Users' perceptions of service quality are influenced by factors such as age, income, preferred mode of travel, tech-savviness, and familiarity with autonomous driving technology.
Chinen et al. 2020	Journal, United State	Survey	passengers' willingness to use emerging mobility services after a sample riding experience is higher than before having a sample riding experience
Guo et al. 2020, 2021	Journal, Sweden	Survey, logit models	The presence of onboard operators has a positive impact on respondents' perceived safety. People who have not taken autonomous buses before have a more negative perception of driving speed of the bus service than people who have taken the buses before. Adverse weather conditions reduce the likelihood of selecting autonomous buses over conventional ones. work-related trips, longer distances, and traveling with companions also increase the preference for conventional buses.
Wu et al. 2021	Journal, China	Survey	Findings revealed positive impacts of attitude on behavioral intention, trust and perceived usefulness on attitudes, while perceived ease of use and comfort influenced usefulness and trust. Notably, perceived risk inversely affected trust.
Mouratidis et al. 2021	Journal, Norway	Survey, interview	Results show that the intention to use the autonomous buses was mostly positive both before and after using them. Most users felt safe while traveling by autonomous bus.
Zhao et al. 2022	Journal, Sweden	Survey	initial attraction linked to sufficient service information while sustained adoption hinges on comfort, frequency, and travel time.
Wintersberger et al. 2022	Book	Survey	trust in/acceptance of autonomous shuttle buses is already high, but indicate also problems, such as a rather low driving speed (less use compared to walking) or unforeseeable maneuvers.
Cheng et al. 2024	Journal, China	Survey and Background	Factors that significantly affect AB adoption intention, include compatibility, relative advantage, safety/security risks, perceived risks, in/out-of-vehicle time, and travel cost.

Table 5: Key studies on Passenger Experience and Design of autonomous buses

The key finding in this context is that the passenger experience in autonomous buses is significantly influenced by factors related to policy, social acceptance, safety, and convenience. Several studies emphasize the importance of comfort, safety, service quality, and convenience as pivotal factors in shaping passengers' attitudes toward autonomous buses. Additionally, the acceptance and long-term adoption of autonomous buses are closely tied to factors like perceived safety, trust, and user experiences in real-world settings, which highlight the intricate and multi-dimensional nature of user acceptance in the context of autonomous bus adoption (Figure 7).

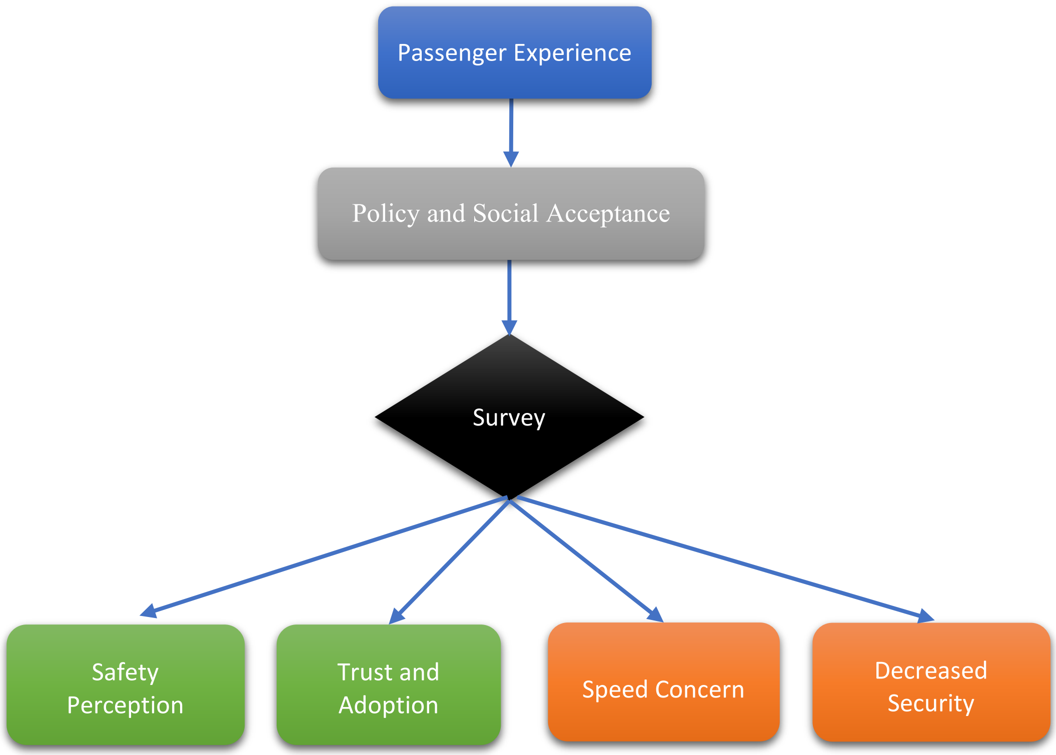

Figure 7. Key Findings of autonomous buses based on Safety and Compliance

4. Conclusion and Future Work

This study systematically reviewed 46 studies on autonomous buses, highlighting that 58% of the research originates outside Europe and the United States, with significant contributions from China, Australia, and Singapore. The findings categorize research into four main areas: Operational Efficiency, Safety and Compliance, Sustainability and Emission, and Passenger Experience. The result shows common methodologies include cost models and simulations, while key objectives focus on optimizing fleet management, resource allocation, and reducing operational expenses. Financial benefits are anticipated, with potential cost reductions, but the findings vary. emphasizes that the cost competitiveness of autonomous buses is not universal but dependent on specific scenarios. Autonomous buses can be more cost-competitive compared to other transportation options, such as autonomous taxis, in specific situations.

It is important to mention that driver-related operating costs representing roughly one-third of the total cost structure for autonomous buses can have a significant financial impact on transitioning to driverless technology. This cost reduction is primarily achieved by eliminating expenses related to driver wages, labor-related expenses, scheduling, turnover, and ongoing monitoring. However, it's essential to weigh these benefits against the initial investment in autonomous technology and maintenance costs to gauge the net financial impact accurately.

Nonetheless, investigations into user acceptance and perceived safety/security consistently reveal that passengers lean toward having personnel present on autonomous buses, potentially offsetting the anticipated cost advantages. As a result, administrators and operators of autonomous bus systems should aim to strike an optimal balance of operational strategies that capture potential benefits (such as cost efficiencies and improved traffic) while effectively tackling security-related apprehensions. Figure 8 summarizes the pros and cons of autonomous buses, highlighting benefits such as cost and emission reductions, alongside challenges like traffic management and security concerns.

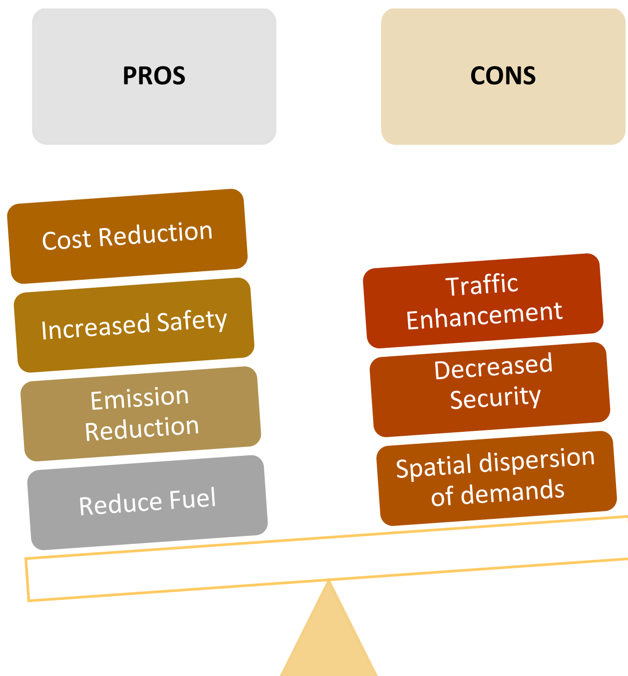

Figure 8. Pros and Cons of using autonomous buses based on the results of studies

Future research should focus on optimizing network design, vehicle resizing, and re-routing traditional transit services. Additionally, integrating autonomous buses as substitutes for conventional ones and assessing their environmental and energy impacts remain critical underexplored areas.

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