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Sustainable Optimization of On-Demand Transportation Systems: Balancing Efficiency and Energy Concerns

Hajar Fatorachian*

Leeds Beckett University, Leeds, LS1 3HB, UK

Abstract

The rapid growth of on-demand transportation services, driven by technological advancements and evolving urban mobility patterns, has significantly transformed urban transportation. However, this shift has highlighted a critical need to understand the interaction between on-demand services and the broader urban transportation ecosystem. This study addresses the challenge posed by the expansion of on-demand transportation, which competes with traditional public transit and raises questions about sustainability and energy efficiency.

This research aims to bridge this gap through an explorative literature review. The methodology involves a systematic review of existing literature on on-demand transportation systems, focusing on themes such as operational efficiency, energy transition, and policy implications. By synthesizing and analyzing this body of literature, the research seeks to uncover insights into the current state of on-demand transportation, identify challenges and opportunities, and suggest directions for future research.

Additionally, this study aims to develop operational and theoretical frameworks to support policy formulation and implementation in urban transportation planning. By integrating findings from existing case studies with insights from the literature, these frameworks will guide policymakers and urban planners in promoting sustainable, energy-efficient on-demand transportation systems. Ultimately, the research aims to contribute to evidence-based policies and practices that support the sustainable development of urban transportation networks in response to changing mobility trends.

The study highlights key insights into the impact of on-demand transportation services on urban mobility, addressing challenges such as operational efficiency, energy transition, and policy implications. It also proposes operational and theoretical frameworks to guide sustainable policy formulation and implementation in urban transportation planning.

* Corresponding author. Tel.: 004407923213685.
E-mail address: h.fatorachian@leedsbeckett.ac.uk

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1. Introduction

Urban transportation is undergoing a significant transformation due to the rise of on-demand transportation services (Docherty et al., 2018; Shaheen et al., 2016). These services, including ride-hailing, customized bus, and shared e-bike options, have reshaped urban mobility patterns (Alonso-González et al., 2020). Enabled by rapid advancements in information and computing technologies, these services offer unprecedented convenience and flexibility to commuters (Choi et al., 2022).

Technological advancements, such as Artificial Intelligence (AI) and the Internet of Things (IoT), have been crucial in enhancing the operational efficiency of on-demand transportation systems (Alsaleh and Farooq, 2021; Shaheen et al., 2016). AI-driven algorithms optimize route planning, demand forecasting, and resource allocation, improving operational efficiency and reducing environmental impact. Similarly, IoT-enabled sensors and connectivity allow for real-time monitoring and management of transportation assets, further enhancing system efficiency and resilience (Fatorachian and Kazemi, 2021; Rajabzadeh and Fatorachian, 2023).

Given the technological revolution, sustainability and energy efficiency have become critical considerations in urban transportation planning (Fatorachian, 2024; Zheng & Zhang, 2017). There is an imperative to mitigate environmental impact, reduce carbon emissions, and manage energy consumption, necessitating a holistic approach to on-demand transportation optimization (Queiroz et al., 2024). Balancing efficiency with energy concerns is a complex challenge, requiring careful navigation of technological innovations, policy interventions, and stakeholder interests (Fatorachian, 2024; Stanley et al., 2011).

This paper addresses this challenge by exploring the relationship between technology, sustainability, and policy in the context of on-demand transportation optimization. Through a thorough review of existing research, the paper aims to identify the operational implications of technological advancements, the challenges and opportunities in integrating on-demand systems with traditional public transit and propose policy frameworks and regulatory interventions for sustainable development. The research questions are as follows:

1. How do advancements in technology, such as AI and IoT, impact the operational efficiency and sustainability of on-demand transportation systems, and what are the implications for urban mobility patterns?
2. What are the key challenges and opportunities in integrating on-demand transportation systems with traditional public transit networks to create a more sustainable and energy-efficient urban transportation ecosystem?
3. How can policy frameworks and regulatory interventions be designed and implemented to promote the sustainable development of on-demand transportation systems, while balancing the needs of users, service providers, and broader urban sustainability goals?

2. Theoretical background

This study is grounded in Sustainable Transportation and Information and Communication Technology (ICT) theories. Sustainable Transportation theory focuses on minimizing the environmental impact of transportation while promoting economic efficiency and social equity, incorporating principles like emissions reduction, energy efficiency, and equitable access (Fatorachian, 2023; Schwanen et al., 2011). ICT theory emphasizes the role of technology in enhancing communication, efficiency, and accessibility within transportation systems, exploring how AI, IoT, and data analytics can optimize resource allocation, improve user experience, and facilitate data-driven decision-making (Lyons, 2018).

2.1. Theories and Concepts in Transportation Systems Optimization

Transportation systems optimization is not merely about improving efficiency, but about navigating the complex, often conflicting goals of sustainability, reliability, and user behavior. Traffic Flow Theory, while foundational in understanding vehicle movement, oversimplifies the unpredictability of real-world traffic congestion dynamics and fails to fully address the growing complexities introduced by autonomous vehicles and changing urban landscapes

(Drew et al., 2020). Network Theory's focus on nodes and links might provide valuable insights into the structural behaviors of transportation systems, but it often neglects the human factors—such as socio-economic disparities—that influence access to these networks (Newman, 2018). Similarly, Multi-Modal Transportation Planning, which promotes seamless integration of different transportation modes, risks falling into the trap of idealism unless bolstered by robust policy interventions and infrastructural investment (Cervero & Kockelman, 1997).

Demand management, often cited as a silver bullet for congestion, can be perceived as punitive, disproportionately impacting lower-income commuters if strategies like congestion pricing aren't implemented with equity in mind (Litman, 2019). In contrast, Smart Transportation Technologies hold significant promise, leveraging ICT advancements for real-time decision-making and enhanced sustainability. However, they are not without their challenges. These technologies, such as Intelligent Transportation Systems (ITS) and connected vehicles, often face hurdles in terms of privacy concerns, data ownership, and technological disparities, which can exacerbate existing inequalities in urban mobility (Zheng et al., 2021; Fatorachian and Kazemi, 2018). Therefore, while these theories and strategies offer substantial potential, a critical approach to their application is essential, particularly in addressing their social and ethical implications.

2.2. Frameworks for Sustainable Urban Transportation Planning

Several frameworks guide sustainable transportation policies and interventions. New Urbanism promotes compact, walkable, and mixed-use development to reduce automobile dependence and encourage active transportation (Calthorpe & Fulton, 2001). Transit-Oriented Development (TOD) focuses on creating dense, mixed-use developments around public transit stations to maximize transit ridership and minimize auto dependency (Cervero, 1998). Complete Streets design aims to accommodate all users, improving safety and multimodal connectivity (National Complete Streets Coalition, 2010). Sustainable Mobility frameworks integrate environmental, social, and economic considerations in transportation planning and decision-making (Agyemang-Duah et al., 2018). Car-Free Cities envision urban environments with minimized or eliminated private automobile use, promoting walking, cycling, and public transit (Hass-Klau, 1990).

3. Methodology

This study employs an explorative literature review methodology to gather and analyze relevant studies, reports, and articles on on-demand transportation systems, sustainability, and energy efficiency. Thematic synthesis and coding of qualitative data extracted from the literature were conducted using NVivo software. Thematic synthesis involved identifying recurring themes and patterns across different studies, while coding facilitated the organization and interpretation of data into meaningful categories (Thomas and Harden, 2008; Saldana, 2009). The synthesized data were analyzed to derive insights and draw conclusions regarding the sustainable optimization of on-demand transportation systems. Inclusion and exclusion criteria for the study are as follows.

Inclusion Criteria:

- Publication Quality: Prioritized high-quality papers published in journals listed in the ABS journal ranking list.
- Relevance to Research Topic: Selected literature specifically addressing the sustainable optimization of on-demand transportation systems.
- Keyword Relevance: Ensured literature contains keywords closely related to the research topic.

Exclusion Criteria:

- Publication Date: Excluded literature published before 2000 to maintain currency and relevance.

The study employed strategies such as adherence to research protocols, naturalistic inquiry, and guidance from established qualitative research methodologies to ensure the credibility and trustworthiness of the findings (Lincoln and Guba, 1985; Denzin and Lincoln, 2011).

4. Current State of On-Demand Transportation Systems

On-demand transportation has significantly transformed urban mobility through various modes such as ride-hailing services (e.g., Uber, Lyft), customized bus services (e.g., Via, Chariot), and shared e-bikes and scooters (e.g., Lime, Bird) (Shaheen et al., 2016; Furuhata et al., 2013; Faghih-Imani et al., 2019). These services have introduced unprecedented convenience and flexibility, reshaping urban travel patterns and offering new solutions for mobility (Fatorachian and Smith, 2022). In Singapore, the GrabShuttle service optimizes routes and schedules based on real-time passenger demand, complementing the public transit network, particularly in areas with limited coverage or during off-peak hours, thereby enhancing operational efficiency (Cheah, 2018). In Denver, Colorado, the Regional Transportation District (RTD) partnered with Uber and Lyft to provide first and last-mile transportation options, improving transit accessibility and operational efficiency through demand-responsive services (Mulley et al., 2020; Fatorachian, 2012). Similarly, Helsinki's Mobility as a Service (MaaS) platform, Whim, integrates various transportation options into a single app, promoting efficient resource use and reducing private car dependency, thus enhancing operational efficiency and sustainability (Tukiainen et al., 2016).

Information, Communication, and Computing Technologies (ICCT) play a crucial role in the operation and management of on-demand transportation systems. Mobile applications, GPS, geospatial data, cloud computing, and data analytics support demand forecasting, pricing optimization, and driver allocation, significantly improving the efficiency and responsiveness of these services (Fatorachian et al., 2013; Hensher & Li, 2019; Vazifeh et al., 2018; Zheng et al., 2019). Furthermore, Artificial Intelligence (AI) and the Internet of Things (IoT) contribute to innovation in on-demand transportation by optimizing ride matching, route planning, and pricing strategies. IoT sensors enable real-time data collection for dynamic service adjustments, further enhancing operational efficiency and responsiveness (Liu et al., 2020; Peters et al., 2021; Rajabzadeh and Fatorachian, 2023).

The COVID-19 pandemic has presented substantial challenges to traditional public transportation systems, leading to declines in ridership, revenue losses, and operational disruptions (Smith and Fatorachian, 2023). To rebuild trust and ensure long-term viability, innovative solutions such as enhanced cleaning protocols and contactless payment options have become necessary (Zachariah et al., 2021; Nieuwenhuijsen et al., 2021).

5. Energy Transition in On-Demand Transportation

The adoption of electric and hydrogen-powered vehicles represents a significant shift towards sustainable energy sources in on-demand transportation. These vehicles offer zero-emission mobility, contributing to air quality improvement and climate change mitigation (Axsen et al., 2020; Wang et al., 2021). The successful integration of renewable energy-powered vehicles relies on the strategic placement of charging stations for electric vehicles (EVs) and hydrogen refueling stations for fuel cell vehicles (FCVs), ensuring accessibility and convenience for both operators and users (Mendes et al., 2020). Additionally, the urban deployment of energy-efficient vehicles necessitates addressing safety concerns related to battery technology, hydrogen storage, and vehicle-infrastructure interaction through rigorous testing, certification, and standardization processes (Bockarjova et al., 2019).

6. Sustainability Challenges and Solutions

Assessing the environmental impact of on-demand transportation involves evaluating greenhouse gas emissions, air quality, and energy consumption through methods such as life cycle assessments, emission modeling, and air quality monitoring (WHO, 2016; USEPA, 2018). To mitigate road congestion and reduce emissions, strategies include promoting shared rides, incentivizing the use of electric vehicles, implementing congestion pricing schemes, and optimizing route planning algorithms (Yang et al., 2019). Evaluating bus priority strategies involves analyzing travel time savings, ridership levels, and customer satisfaction, as well-designed bus priority measures can improve transit reliability and reduce travel times (Cats et al., 2021). Enhancing transport efficiency requires integrating micromobility options, deploying autonomous vehicles, and implementing demand-responsive transit services (Buldeo Rai et al., 2020).

7. Data-Driven Optimization Techniques

High-quality data is essential for optimizing on-demand transportation systems. Accurate data on travel demand, traffic patterns, vehicle availability, and user preferences enable informed decisions (Hollis et al., 2020). Data analytics and machine learning algorithms optimize routes by analyzing historical trip data, real-time traffic conditions, and spatial characteristics, minimizing travel time, distance, and fuel consumption (Zhang et al., 2019). Predictive modeling leverages historical data to forecast future demand for on-demand transportation services, enabling efficient resource allocation based on factors such as time, weather, and events (Wang et al., 2021).

8. Policy Implications, Practice, and Recommendations

Sustainable transportation goals should be integrated into comprehensive urban policy frameworks to promote environmentally friendly, equitable, and efficient mobility solutions. This involves setting targets for reducing fossil fuel reliance and increasing the use of renewable energy-powered transportation modes (Litman, 2019). Urban planners, transportation authorities, and policymakers must collaborate closely to develop integrated transportation strategies that prioritize sustainability, equity, and resilience. This includes investing in infrastructure improvements, expanding public transit networks, and incentivizing energy-efficient transportation technologies (Zheng et al., 2021). Evidence-based decision-making is crucial for informing policy development and evaluating transportation interventions. Policymakers and urban planners should rely on high-quality data and rigorous analysis to understand trends, assess impacts, and identify areas for improvement (Pekel et al., 2017). Policy interventions should prioritize initiatives that reduce emissions, enhance energy efficiency, and improve sustainability. Recommended actions include setting emissions standards, providing subsidies for electric vehicles, and investing in renewable energy infrastructure (Litman, 2019).

9. Operational Framework

The operational framework presented in this section aims to address the research questions by outlining a comprehensive approach to the sustainable development and integration of on-demand transportation systems. This framework is designed to guide policymakers, urban planners, and transportation authorities in promoting operational efficiency, energy sustainability, and equitable access within urban mobility networks.

By following this operational framework, urban planners and policymakers can effectively address the research questions and promote the sustainable development of on-demand transportation systems. This approach ensures that technological advancements, sustainability goals, and user needs are harmoniously integrated to create efficient, equitable, and environmentally friendly urban mobility solutions.

Figure 1 illustrates a comprehensive framework for optimizing and improving transportation or infrastructure systems, emphasizing sustainability, efficiency, and equity. The core elements include Enhancing Operational Efficiency, Promoting Energy Sustainability, and Ensuring Equitable Access. These objectives are supported by Technology Integration, Sustainability Measures, and Infrastructure Development, all of which are tested through Pilot Programs and Testing. The process is monitored and evaluated through Monitoring and Evaluation, Impact Assessments, and Feedback Mechanisms. Continuous feedback loops, driven by Data Collection and Analysis, enable Continuous Improvement, ensuring the system evolves and improves over time. Stakeholder Engagement is crucial at every stage, ensuring that diverse perspectives are integrated into the decision-making process. Overall, the diagram underscores a cyclical and iterative approach to achieving sustainable and efficient transportation or infrastructure systems, emphasizing the importance of feedback and stakeholder involvement.

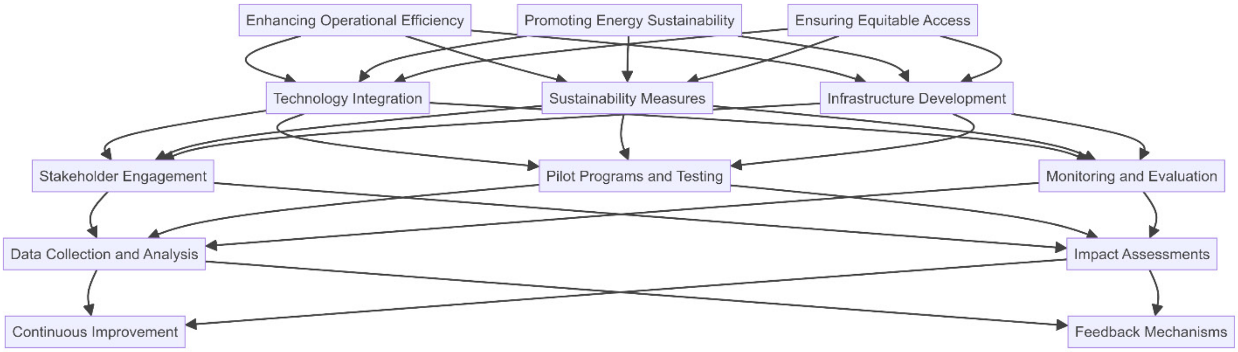

Figure 1. Developed framework

10. Discussion and Conclusion

This study has highlighted the critical role of technological advancements in shaping on-demand transportation. Innovations in AI and IoT have significantly enhanced operational efficiency, route optimization, and service responsiveness, demonstrating their transformative potential in urban mobility. These technologies not only improve the user experience but also contribute to reducing environmental impacts by optimizing resource use and minimizing emissions.

The research has also explored the challenges and opportunities in integrating on-demand transportation with traditional public transit. While on-demand services offer flexibility and convenience, their successful integration with existing transit networks is essential for creating a cohesive and efficient urban transportation system. Case studies from Singapore, Denver, and Helsinki illustrate various strategies for achieving this integration, such as leveraging real-time data for route planning and establishing partnerships between public and private transportation providers. These examples underscore the potential for on-demand services to complement and enhance traditional transit, particularly in addressing first and last-mile connectivity.

Moreover, the study emphasized the importance of robust policy frameworks and regulatory interventions. Effective policies are crucial for promoting sustainable and equitable transportation solutions. This includes setting emissions standards, providing incentives for the adoption of renewable energy-powered vehicles, and ensuring that transportation services are accessible to all segments of the population. Regulatory measures must balance the needs of users, service providers, and the broader community to achieve sustainable urban mobility.

Addressing sustainability challenges requires a multifaceted approach that considers environmental, social, and economic dimensions. The transition to renewable energy-powered vehicles, strategic infrastructure development, and the implementation of data-driven optimization techniques are vital components of this approach. Additionally, assessing the environmental impact of on-demand transportation through life cycle assessments and emission modeling is essential for developing strategies to mitigate congestion and reduce emissions.

Future research should focus on several key areas to develop comprehensive solutions that balance sustainability, efficiency, and accessibility in urban mobility systems. First, long-term environmental impacts of on-demand transportation need to be thoroughly investigated to understand the broader implications of these services on urban ecosystems. Second, deeper exploration of technological integration with public transit will provide insights into how these systems can work synergistically. This includes examining the role of emerging technologies, such as autonomous vehicles, in enhancing service efficiency and sustainability. Third, equity considerations must be prioritized to ensure that transportation solutions are inclusive and accessible to all, particularly underserved and marginalized communities.

By considering technological advancements, integration challenges, and policy frameworks, we can pave the way for sustainable, energy-efficient, and accessible urban mobility solutions. Policymakers, urban planners, and transportation authorities must collaborate to implement innovative strategies that address the complex dynamics of urban transportation. This collaborative effort will be instrumental in shaping the future of urban mobility, ensuring that it meets the evolving needs of cities and their inhabitants while promoting environmental stewardship and social equity. Ultimately, the insights gained from this study provide a foundation for developing resilient and adaptable transportation systems that can thrive in the face of emerging challenges and opportunities.

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