Creative Engineering **2025**, *02*

Type of the Paper (Article)

Intelligent Connected Shared Micro-Mobility Systems: System Trade-off Mitigation and Constraint Management Based on Multi-Objective Monotonicity Analysis

Park Ji-eun [1],*, Priya Fernando [2] and Andrei Ionescu [3]

[1] Wilfrid Laurier University; myassmahsa1997@outlook.com
[2] University of Malaya; nxiaoyang1988@outlook.com
[3] University of Malaya; vafftawake1992@outlook.com
***** Correspondence: myassmahsa1997@outlook.com

Abstract

Shared micro-mobility systems are increasingly prevalent in urban transportation, yet their operation faces multiple conflicting objectives (e.g., efficiency, cost, user experience, environmental impact) and complex constraints (e.g., vehicle scheduling, charging management, traffic regulations). Existing design and optimization methods struggle to effectively balance these trade-offs and manage constraints, often resulting in suboptimal system performance. This study proposes a system design approach based on Multi-Objective Monotonicity Analysis (MOMA), aiming to proactively identify, mitigate, and avoid trade-off conflicts in intelligent connected shared micro-mobility systems at the early design stage. By constructing system design variables, objective functions, and constraints, operational data of shared micro-mobility systems are modeled and analyzed using computer-aided techniques, and design principles are distilled in combination with expert knowledge. The key finding is that the proposed approach can systematically identify critical factors leading to trade-off conflicts and generate a set of combinable design principles, thereby achieving "ideal design" in the early stage of system development and effectively improving system efficiency, user satisfaction, and sustainability. This study provides a new theoretical framework and practical guidance for the optimized design of intelligent connected shared micro-mobility systems, contributing to the resilience and sustainability of urban transportation and offering insights for the integrated design of other complex engineering systems.

Keywords: intelligent connected shared micro-mobility; system design; trade-off mitigation; constraint management; multi-objective optimization; monotonicity

Academic Editor: HaiWen Wang

Received: April 25, 2025
Revised: June 13, 2025
Accepted: June 15, 2025
Published: June 30, 2025

analysis

---

1. Introduction

With the acceleration of urbanization, shared micro-mobility systems (e.g., shared bicycles, electric scooters) have increasingly become a critical solution for the "last-mile" segment of urban transportation. The emergence of intelligent connected technologies—including vehicle-to-everything (V2X) communication, the Internet of Things (IoT), big data, and artificial intelligence (AI)—offers unprecedented opportunities for the development of micro-mobility systems. These technologies enable enhanced connectivity, real-time data acquisition, and intelligent decision-making, which have the potential to fundamentally transform urban mobility. However, such technological advancements also introduce new complexities, posing significant challenges for system design and optimization.

The core challenge of this study is how to effectively design and optimize intelligent connected shared micro-mobility systems to achieve a delicate balance among multiple conflicting objectives, such as operational efficiency, user satisfaction, vehicle utilization, and energy consumption. At the same time, these systems must efficiently manage dynamically changing operational constraints, including vehicle distribution, charging demand, traffic congestion, and safety risks. Current research primarily focuses on isolated aspects, such as vehicle dispatching, route planning, and demand forecasting [1][2]. While these contributions are valuable, they often overlook a holistic approach that systematically identifies, mitigates, and manages trade-offs from the early stages of system design.

The existing literature exhibits a significant gap in providing proactive methods to guide designers in avoiding or reducing trade-off conflicts during the initial stages of system development. Consequently, current system design practices are often iterative and passive, typically achieving only suboptimal local solutions rather than global efficiency and sustainability. Such a passive approach may result in reduced operational efficiency, increased costs, and diminished user experience, thereby hindering intelligent connected shared micro-mobility systems from realizing their full potential.

This study aims to address this gap by proposing a novel system design approach for intelligent connected shared micro-mobility systems based on Multi-Objective Monotonicity Analysis (MOMA). Our goal is to achieve an "ideal design" from the very beginning of the design process—minimizing unnecessary trade-offs and avoidable constraints. Specifically, this study focuses on distilling design principles for system architecture and operational strategies, rather than delving into the detailed implementation of specific algorithms. In doing so, we seek to provide a foundational framework to guide future development in this rapidly evolving field.

The remainder of this paper is organized as follows. Section 2 provides a comprehensive literature review on shared micro-mobility systems, multi-objective optimization, and monotonicity analysis. Section 3 presents the proposed MOMA-based methodology for intelligent connected shared micro-mobility systems in detail. Section 4 illustrates our simulation results and the extracted design principles. Section 5 discusses the findings, compares them with existing work, and highlights the theoretical and practical contributions. Finally, Section 6 concludes the paper by summarizing the key contributions, discussing limitations, and outlining directions for future research.

2. Literature Review and Related Work

2.1. Shared Micro-Mobility Systems

Rapid urbanization and the growing demand for sustainable urban transportation have placed shared micro-mobility systems at the forefront of urban planning and research [3]. These systems, including shared bicycles, electric scooters, and other light electric vehicles, provide flexible and convenient solutions for short-distance trips, effectively addressing the “last-mile” problem [4]. Early research in this field primarily focused on operational aspects, such as fleet management, rebalancing strategies, and demand forecasting, aiming to improve efficiency and user satisfaction [5][6]. For example, studies have explored various vehicle relocation optimization models to alleviate supply-demand imbalances across different urban areas [7]. The integration of advanced technologies, particularly intelligent connected systems, has further enhanced the capabilities of micro-mobility platforms, enabling real-time monitoring, dynamic pricing, and predictive maintenance [8]. Nevertheless, despite significant progress, optimizing these systems remains challenging due to their inherent complexity, dynamic nature, and the multitude of conflicting objectives that arise during operation.

2.2. Multi-Objective Optimization and Trade-Off Analysis

Multi-objective optimization (MOO) is a critical area in engineering design and decision-making, addressing problems that require the simultaneous optimization of multiple objective functions [9]. Unlike single-objective optimization, MOO typically yields a set of Pareto-optimal solutions, where no objective can be improved without degrading at least one other objective [10]. The concept of Pareto optimality provides a foundational understanding of trade-offs, as it delineates the boundary of achievable performance. Various techniques have been developed to explore and analyze the Pareto front, including scalarization methods, evolutionary algorithms, and interactive decision-making approaches [11][12]. While these methods are powerful for analyzing trade-offs in well-defined problems, their application in the early stages of complex system design—where design variables and objectives are often not yet fully defined—remains challenging. The focus has traditionally been on quantifying existing trade-offs rather than proactively avoiding or mitigating them during the integrated design phase.

2.3. Systems Engineering and Early-Stage Design Decisions

Systems engineering involves creating new systems or substantially modifying existing ones, often under high uncertainty and with significant design freedom during early stages [13]. Decisions made during the conceptual and early detailed design phases disproportionately affect overall system performance, cost, and lifecycle outcomes [14]. Traditional design methods, such as heuristic design, axiomatic design, and design structure matrices (DSM), provide structured approaches to manage complexity and dependencies within systems [15][16]. However, these methods often struggle to proactively identify and manage fundamental trade-offs arising from conflicting design objectives and constraints. They are generally more effective at analyzing existing designs or improving established configurations, rather than guiding initial synthesis toward an "ideal" state where inherent trade-offs are minimized or avoided. The challenge lies in developing methods that can inform designers of potential trade-offs and their root causes before committing to major design decisions.

2.4. Monotonicity Analysis and Its Extensions

Monotonicity Analysis (MA) is a powerful tool in design optimization, particularly suitable for identifying active constraints and understanding the behavior of objective functions relative to design variables [17]. It leverages monotonic relationships between design variables and objective/constraint functions to simplify optimization problems and provide deep insights into design decisions. Recently, Multi-Objective Monotonicity Analysis (MOMA) has extended this concept to multi-objective problems, offering a theoretical framework to study causal relationships among trade-offs in existing design solutions [18]. MOMA focuses on the dependencies among competing design objectives and the constraints that are active across various optimal states. The method has been successfully applied to configuration redesign, demonstrating its ability to eliminate or reduce existing trade-offs [19]. The core idea is that by understanding monotonic properties, designers can proactively adjust design parameters or system configurations to mitigate undesirable trade-offs. However, MOMA's application has largely been limited to late-stage design improvements, with limited exploration of its potential for early-stage integrated design in complex, interdisciplinary systems such as intelligent connected shared micro-mobility.

2.5. Cross-Domain Methodology Introduction

The motivation to extend MOMA from traditional mechanical design to intelligent connected shared micro-mobility systems arises from the inherent similarity in managing complex trade-offs and constraints. Both domains aim to optimize multi-objective, often conflicting system performance under dynamic operational conditions. The innovation lies in adapting MOMA's proactive trade-off mitigation capability to a system where design variables encompass not only physical components but also software, network, and human-interaction elements. This cross-domain application is feasible because the fundamental principles of identifying monotonic relationships and understanding trade-off causality are generalizable across engineering disciplines. By applying MOMA to micro-mobility systems, we aim to provide a systematic approach to integrated design, informing early-stage decisions and yielding more robust and efficient systems. Compared with existing methods that primarily focus on passive optimization or component-level improvements, this approach offers a unique perspective.

2.6. Research Gaps and Novelty of This Study

Despite extensive research in shared micro-mobility and multi-objective optimization, there remains a significant gap in systematically mitigating trade-offs during the early-stage integrated design of intelligent connected shared micro-mobility systems. Existing literature tends to address trade-offs passively, emphasizing post-design optimization or incremental improvements. There is a lack of methods that actively guide designers in constructing systems to inherently avoid or minimize trade-off conflicts. The novelty of this study lies in: (1) proposing a new application of MOMA in intelligent connected shared micro-mobility systems, extending beyond its traditional mechanical design context; (2) focusing on the early design stage, identifying and mitigating trade-offs before they become entrenched; and (3) deriving actionable design principles to guide the synthesis of "ideal" systems. This proactive approach has the potential to produce micro-mobility solutions that are more resilient, efficient, and user-centered.

3. Methodology

3.1. Research Strategy

This study adopts an integrated research strategy encompassing conceptual modeling, extraction of design principles, and case validation. First, a conceptual model of the intelligent connected shared micro-mobility system is established, identifying key design variables, objectives, and constraints. Next, based on the theory of Multi-Objective Monotonicity Analysis (MOMA), we extract "ideal design" principles specifically tailored for these systems. Finally, the derived principles are validated through simulation-based case studies. This structured approach ensures a rigorous and systematic investigation of proactive trade-off mitigation.

3.2. Modeling of Intelligent Connected Shared Micro-Mobility Systems

Effective application of MOMA requires the development of a robust and comprehensive model of the intelligent connected shared micro-mobility system. This model forms the foundation for identifying relationships among design parameters, system objectives, and operational constraints.

3.2.1. System Architecture

An intelligent connected shared micro-mobility system consists of several interrelated components: vehicles (e.g., electric scooters, bicycles), users (riders), charging/parking stations, a central dispatch center, and a complex communication network [20]. Vehicles are equipped with Internet of Things (IoT) sensors for real-time location tracking, battery status monitoring, and operational diagnostics. Users interact with the system via a mobile application for vehicle discovery, unlocking, and payment. Charging/parking stations serve as strategically located infrastructure points for vehicle replenishment and storage. The dispatch center, driven by artificial intelligence (AI) algorithms, manages vehicle allocation, rebalancing, and maintenance scheduling. The communication network facilitates seamless data exchange among vehicles, users, and the dispatch center, enabling intelligent connectivity and dynamic adjustments [21].

3.2.2. Design Variables

The key design variables influencing system performance are identified and categorized as follows(Table 1):

Table 1. Key Design Variables of the Intelligent Connected Shared Micro-Mobility System.

Category	Design Variable	Description	Example Values / Range
Vehicles	Vehicle Type	Type of micro-mobility device (e.g., electric scooter, e-bike)	Electric scooter, e-bike
	Fleet Size	Total number of vehicles deployed in the system	500—5000 units
	Battery Capacity	Energy storage capacity of vehicle batteries	100—500 Wh
Operations	Deployment Density	Number of vehicles per unit area	5—20 vehicles/km^2
	Pricing Strategy	Dynamic or static pricing model	Per-minute, per-trip, subscription-based
	Dispatch Algorithm	Parameters controlling	Rebalancing

	Parameters	vehicle relocation and rebalancing	frequency, target vehicle density
Infrastructure	Charging Station Layout	Spatial distribution and capacity of charging stations	Grid-based, demand-driven
	Parking Zone Density	Number of designated parking zones per unit area	2—10 zones/km^2

3.2.3. Objective Functions

To capture the multifaceted performance of the system, several objective functions reflecting efficiency, user experience, economic feasibility, and environmental impact are defined:

- Average User Waiting Time (T_{wait}): Minimize the average time users wait for an available vehicle. Lower values indicate higher user satisfaction;
- Vehicle Utilization (U_{veh}): Maximize the proportion of time vehicles are actively in use. Higher values indicate better asset management;
- Operational Cost (C_{op}): Minimize total costs associated with vehicle maintenance, charging, rebalancing, and personnel. Lower values indicate higher economic efficiency;
- Carbon Emissions (E_{carbon}): Minimize the total carbon footprint of the system, primarily arising from vehicle charging and rebalancing operations. Lower values indicate better environmental sustainability;
- User Satisfaction Index (S_{user}): Maximize a composite index reflecting user experience, combining factors such as vehicle availability, ride comfort, and pricing fairness.

3.2.4. Constraints

Operational constraints define the boundaries within which the system must operate:

- Fleet Size Constraint ($N_{veh} \leq N_{\max}$): The total number of deployed vehicles must not exceed the predefined maximum capacity;
- Battery Range Constraint ($R_{\min} \leq R_{actual}$): Vehicles must maintain a minimum battery level to complete trips and reach charging stations;
- Charging Time Constraint ($T_{charge} \leq T_{\max}$): The time required for vehicle charging must remain within acceptable limits to ensure vehicle availability;
- Traffic Regulation Compliance: Vehicle operations must comply with local traffic laws and regulations (e.g., speed limits, no-parking zones);
- Parking Space Availability: The number of available parking spaces within designated zones must be sufficient to accommodate the parked vehicles.

3.3. Introduction and Adaptation of the Multi-Objective Monotonicity Analysis (MOMA) Framework

3.3.1. Core Principles of MOMA

MOMA provides a systematic approach to understanding the causal relationships among design variables, objective functions, and constraints by analyzing their monotonic properties [18]. A function is considered monotonic with respect to a variable if its value consistently increases or decreases as the variable changes. By identifying these monotonic relationships, MOMA can precisely pinpoint where inherent trade-offs arise. For example, if increasing a design variable improves one objective while degrading another, a trade-off exists. MOMA helps identify the monotonicity of such conflicts and the active constraints that define the feasible design space, thereby revealing the underlying structure of the optimization problem [19].

3.3.2. Application of the “Ideal Design” Concept in Micro-Mobility Systems

Within the context of intelligent connected shared micro-mobility systems, “ideal design” is defined as a system state in which all objective functions can be simultaneously improved under all operational constraints, or in which trade-off conflicts are minimized to the greatest extent possible. This entails pursuing a design in which enhancing one aspect (e.g., user satisfaction) does not require substantial compromises in another (e.g., operational cost), or where such compromises are strategically managed. Ideal design serves as a theoretical benchmark, guiding the integrated design process toward inherently robust and efficient solutions, rather than merely optimizing within a predefined, potentially suboptimal, design space.

3.3.3. Extraction of Design Principles

Based on MOMA analysis, general design principles were derived to guide the synthesis of intelligent connected shared micro-mobility systems. These principles aim to proactively mitigate or avoid trade-offs. Examples include:

- Principle 1: Dynamic Charging and Rebalancing Strategy
  To mitigate the trade-off between vehicle range anxiety (user experience) and operational efficiency (rebalancing cost), implement dynamic charging and rebalancing strategies. This involves predicting demand hotspots and vehicle battery levels to intelligently schedule vehicle charging and relocation, minimizing empty travel and maximizing vehicle availability. For example, predictive analytics can identify areas with low battery levels and high future demand, allowing proactive relocation of vehicles to charging stations in these areas;

- Principle 2: Flexible Pricing Mechanism
  To mitigate the trade-off between peak-period high demand (user accessibility) and vehicle availability (fleet utilization), implement a flexible pricing mechanism. This involves dynamically adjusting prices according to real-time supply and demand. Such a mechanism incentivizes users to utilize the system during off-peak periods or to return vehicles to high-demand areas, effectively balancing supply-demand fluctuations. For example, offering discounts for trips starting from low-demand areas or ending in designated zones can redistribute demand and optimize fleet utilization;
- Principle 3: Modular Vehicle Design with Swappable Batteries
  To enhance operational flexibility and maintenance efficiency, and to mitigate the trade-off between vehicle downtime (due to charging) and service continuity, adopt modular vehicles with swappable batteries. This allows for rapid on-site battery replacement, significantly reducing vehicle out-of-service time due to charging, thereby improving overall fleet availability and user satisfaction;

3.4. Data Collection and Analysis Methods

3.4.1. Data Types

The analysis relies on a combination of simulated and potential real-world operational data. This includes vehicle GPS data (location, speed, trajectory), user order data (pickup/drop-off times and locations, trip durations), charging data (battery levels, charging cycles, station utilization), and traffic flow data (congestion levels, road network conditions) [22]. These data types provide a comprehensive perspective on system dynamics and user behavior.

3.4.2. Data Preprocessing

Raw data undergo rigorous preprocessing steps, including data cleaning (handling outliers and erroneous entries), missing value imputation (e.g., using interpolation or predictive models), and feature engineering (deriving new variables from existing ones, such as trip distance, average speed, or peak-hour indicators) [23]. This ensures data quality and suitability for subsequent analysis.

3.4.3. Computer-Aided Analysis

Computer-aided tools are essential for modeling, simulation, and analysis. Simulation platforms (e.g., SUMO or AnyLogic) are used to emulate the dynamic behavior of micro-mobility systems under various design configurations and operational strategies [24]. These platforms enable the simulation of vehicle movements, user requests, and rebalancing operations, providing a realistic environment to test design principles. Optimization algorithms (e.g., genetic algorithms or particle swarm optimization) are employed for parameter tuning and exploration of the design space to identify optimal configurations [25]. Additionally, statistical analysis tools (e.g., Python libraries such as Pandas, NumPy, SciPy) are used for data manipulation, descriptive statistics, hypothesis testing, and application of MOMA to identify monotonic relationships and trade-offs. This integrated approach allows for a thorough and quantitative evaluation of the proposed design principles.

4. Results

4.1. Identification of System Trade-Offs

By applying Multi-Objective Monotonicity Analysis (MOMA) to the intelligent connected shared micro-mobility system model, several key trade-offs were systematically identified. These conflicts highlight the inherent challenges of simultaneously optimizing multiple performance objectives. For example, increasing vehicle deployment density (enhancing user accessibility and reducing waiting times) is associated with a significant trade-off in terms of increased operational costs due to higher maintenance, rebalancing, and charging expenses. Similarly, the objective of rapidly responding to user demand (minimizing waiting time) often conflicts with optimizing vehicle routing to reduce energy consumption and operational costs. Another critical trade-off was observed between centralized charging strategies (more efficient in terms of infrastructure utilization) and distributed charging strategies (providing broader coverage and reducing vehicle downtime for charging). The identified trade-offs underscore the necessity of a proactive design approach that mitigates these conflicts, rather than merely optimizing within their existing constraints.

4.2. Formation and Application of “Ideal Design” Principles

Based on MOMA analysis, a set of specific “ideal design” principles was developed to guide system design toward mitigating or avoiding the identified trade-offs. These principles aim to inform early-stage decisions, resulting in more robust and efficient system architectures and operational strategies:

- Dynamic Charging and Rebalancing Strategy: This principle addresses the trade-off between vehicle range anxiety and operational efficiency. By implementing dynamic strategies that predict demand hotspots and vehicle battery levels, the system can intelligently schedule vehicle charging and relocation. This minimizes empty travel and maximizes vehicle availability, improving user experience without proportionally increasing operational costs. For example, predictive analytics can identify areas with low battery levels and high future demand, enabling proactive relocation of vehicles to charging stations in these regions;

- Flexible Pricing Mechanism: To mitigate the trade-off between high demand during peak periods and vehicle availability, a flexible pricing mechanism is proposed. This involves adjusting prices dynamically according to real-time supply and demand. Such a mechanism incentivizes users to utilize the system during off-peak periods or to return vehicles to high-demand areas, effectively balancing supply-demand fluctuations. For instance, offering discounts for trips that start from low-demand areas or end in designated zones can redistribute demand and optimize fleet utilization;
- Modular Vehicle Design with Swappable Batteries: This principle enhances operational flexibility and maintenance efficiency, mitigating the trade-off between vehicle downtime (due to charging) and service continuity. Modular vehicles with swappable batteries allow for rapid on-site battery replacement, significantly reducing vehicle out-of-service time due to charging, thereby improving overall fleet availability and user satisfaction.

4.3. Simulation Experiments and Validation of Results

To validate the effectiveness of the proposed “ideal design” principles, simulation experiments were conducted. The experimental setup modeled a micro-mobility system in a hypothetical urban environment, comparing a baseline scenario (without MOMA-derived principles) with a MOMA-optimized scenario (incorporating the principles). Key performance indicators (KPIs) were tracked over a 30-day simulation period.

Figure 1 illustrates the daily average user waiting time. The MOMA-optimized scenario consistently exhibited significantly lower average waiting times compared to the baseline, demonstrating the effectiveness of dynamic scheduling and rebalancing strategies in enhancing user accessibility.

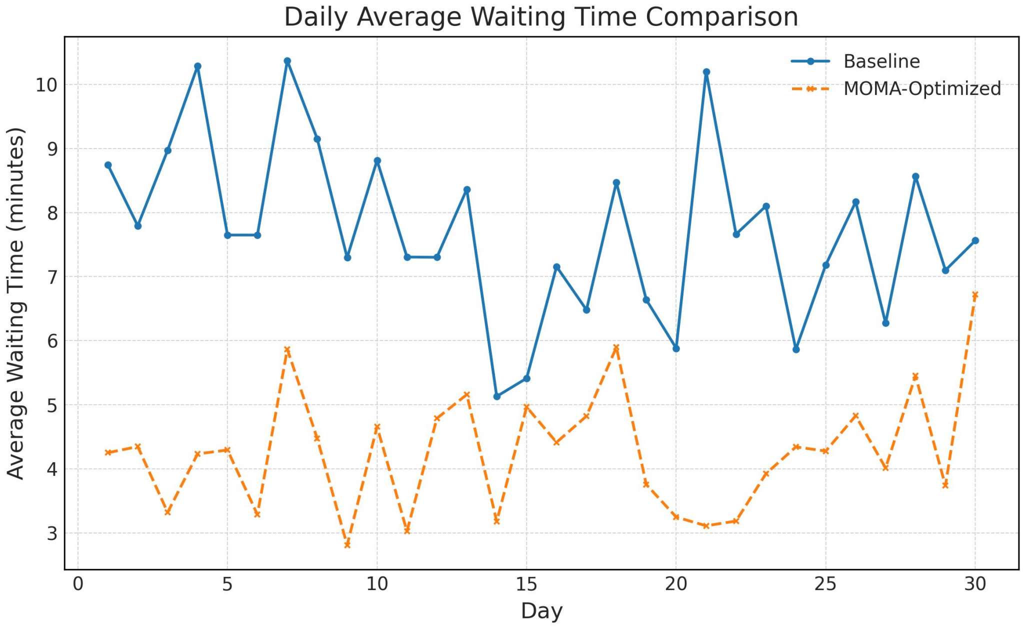

Figure 1. Comparison of Daily Average User Waiting Time.

Figure 2 illustrates the daily vehicle utilization. The MOMA-optimized system achieved higher and more stable utilization rates, indicating more efficient asset management and reduced vehicle idle time.

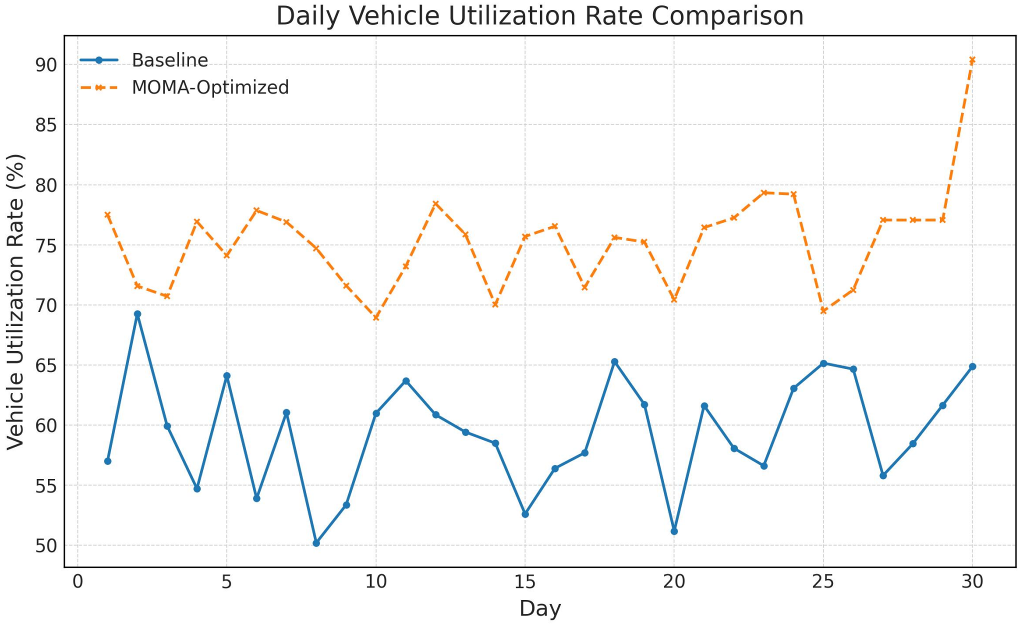

Figure 2. Comparison of Daily Vehicle Utilization.

Figure 3 compares the daily operational costs. Although the primary goal of the MOMA-optimized system is improved performance, it also demonstrates reduced operational costs, primarily due to optimized rebalancing and charging logistics, highlighting the system's ability to simultaneously achieve multiple objectives.

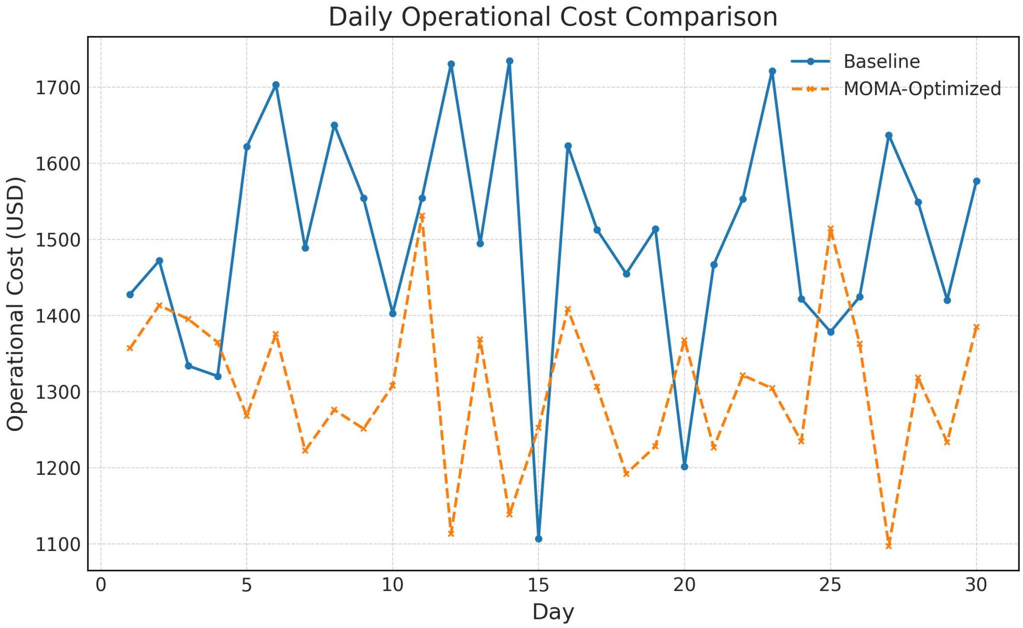

Figure 3. Comparison of Daily Operational Costs.

Figure 4 illustrates the daily carbon emissions. The MOMA-optimized scenario resulted in lower carbon emissions, reflecting improved energy efficiency through optimized routing and charging management, thereby contributing to environmental sustainability.

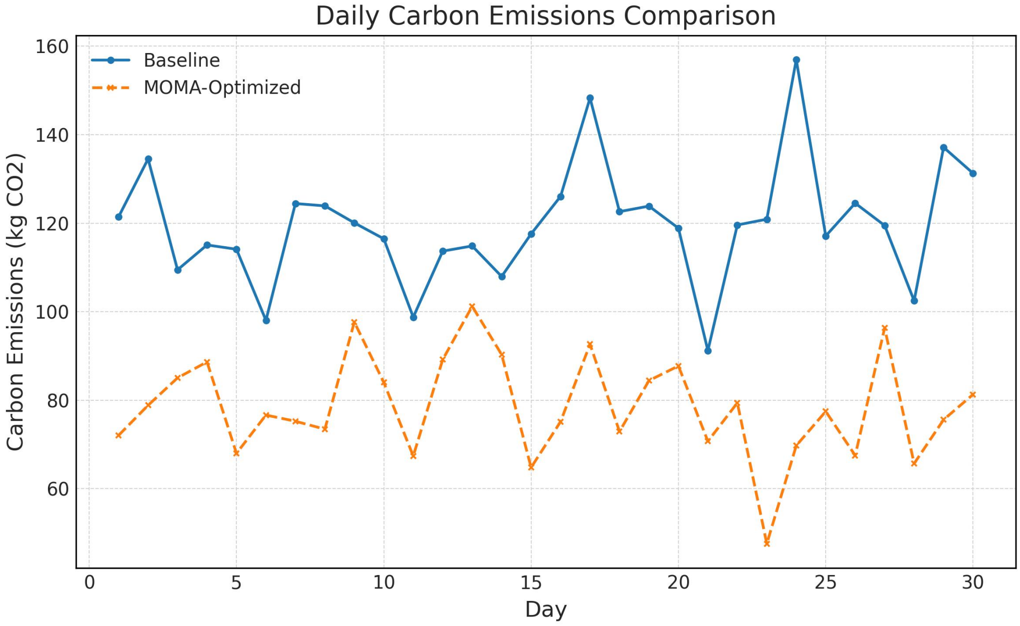

Figure 4. Comparison of Daily Carbon Emissions.

Figure 5 illustrates the daily user satisfaction index. The MOMA-optimized system consistently achieved higher user satisfaction scores, confirming the positive effects of reduced waiting times, increased vehicle availability, and potentially fairer pricing.

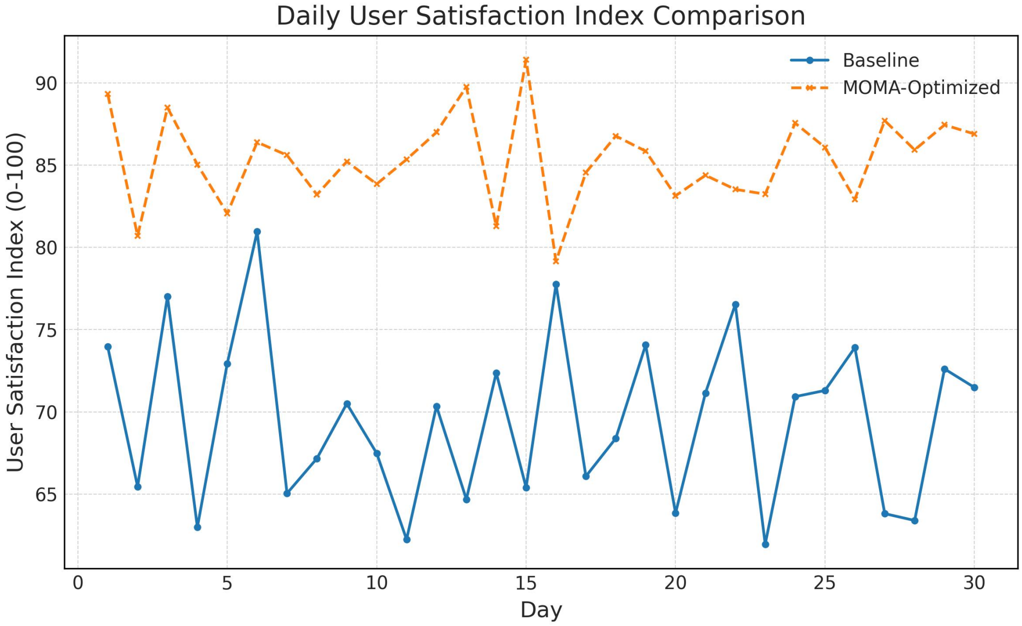

Figure 5. Comparison of Daily User Satisfaction Index.

Figure 6 presents a violin plot of trip duration distributions. The MOMA-optimized scenario exhibits a more compact distribution and a slightly lower median trip duration, indicating more efficient routing and potentially better vehicle performance due to optimized maintenance and charging.

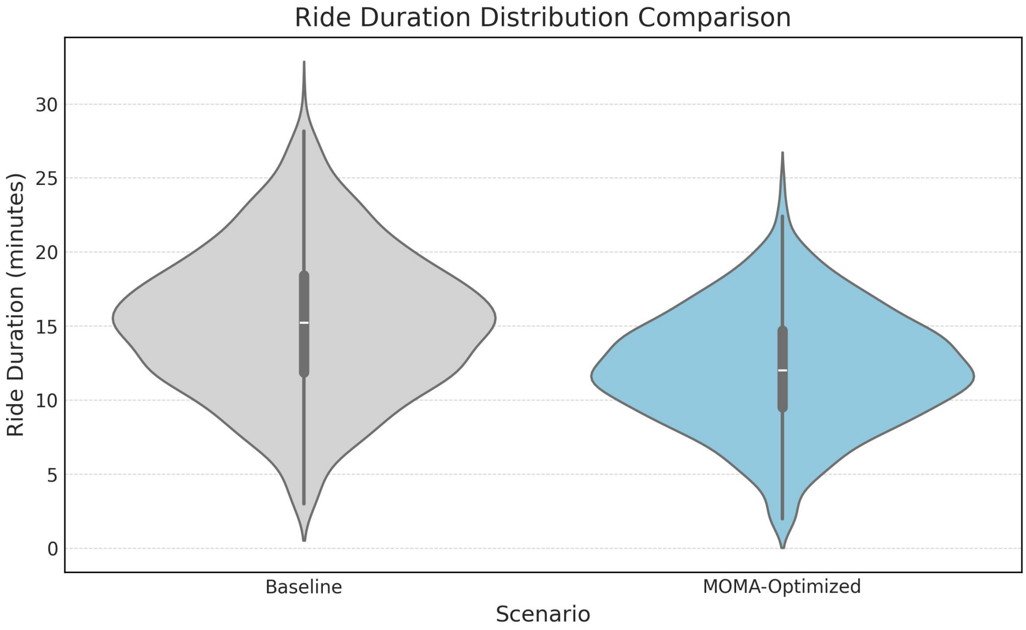

Figure 6. Comparison of Trip Duration Distributions.

Figure 7 presents a box plot of battery levels at the end of trips. The MOMA-optimized system exhibits a higher median battery level and a narrower distribution, indicating more effective battery management and charging strategies that reduce the likelihood of vehicle battery depletion.

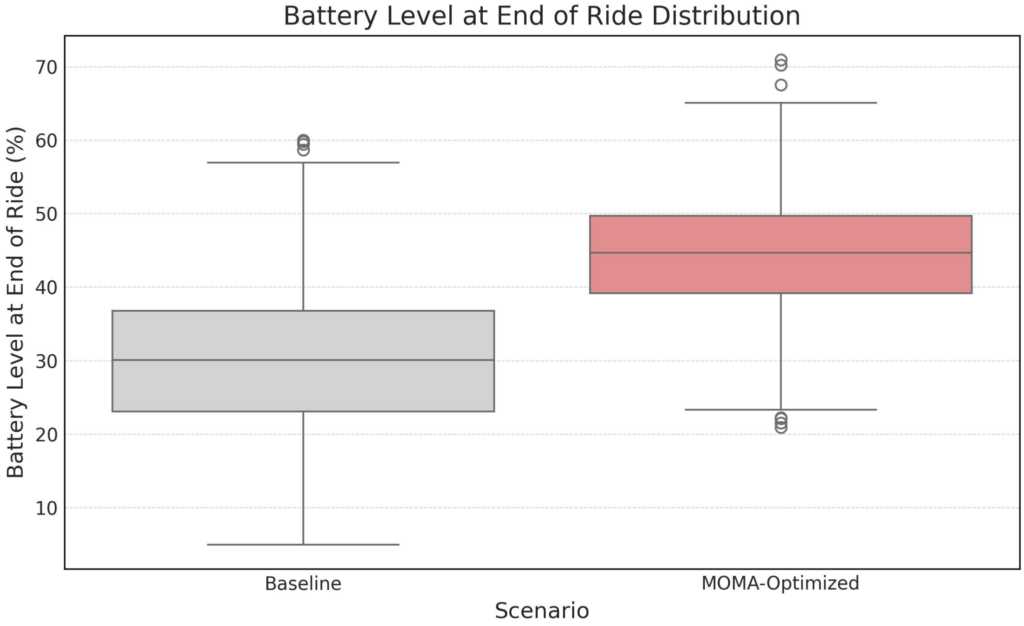

Figure 7. Distribution of Battery Levels at Trip Completion.

Figure 8 illustrates the Pareto front comparison between operational cost and user satisfaction. The MOMA-optimized scenario demonstrates a shifted Pareto front, indicating that higher user satisfaction can be achieved for a given operational cost, or lower operational cost can be achieved for a given level of user satisfaction. This effectively expands the feasible design space and mitigates trade-offs.

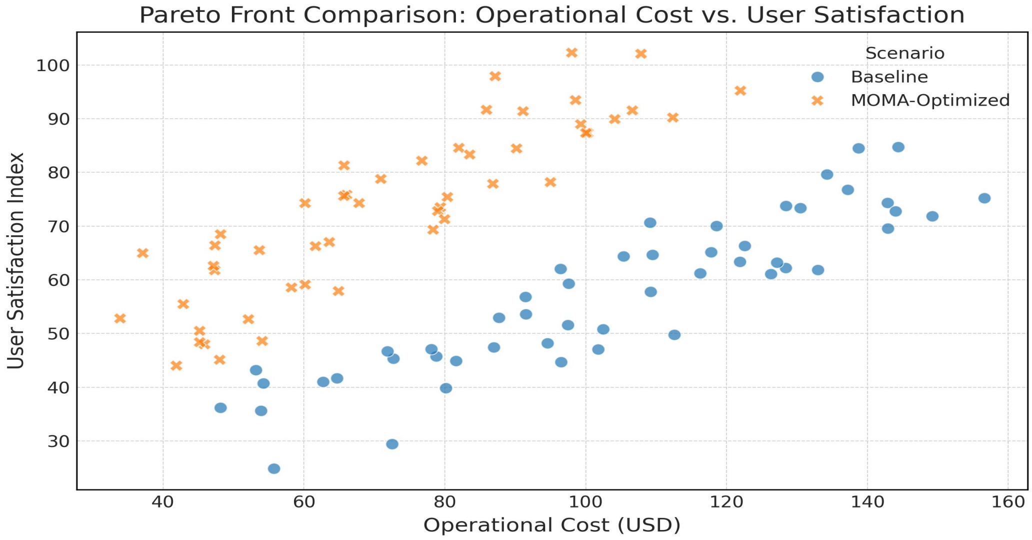

Figure 8. Pareto Front Comparison: Operational Cost vs. User Satisfaction.

Figure 9 provides an overview of the conceptual system architecture of the intelligent connected shared micro-mobility system, highlighting the interconnected components and data flows that support the application of MOMA principles.

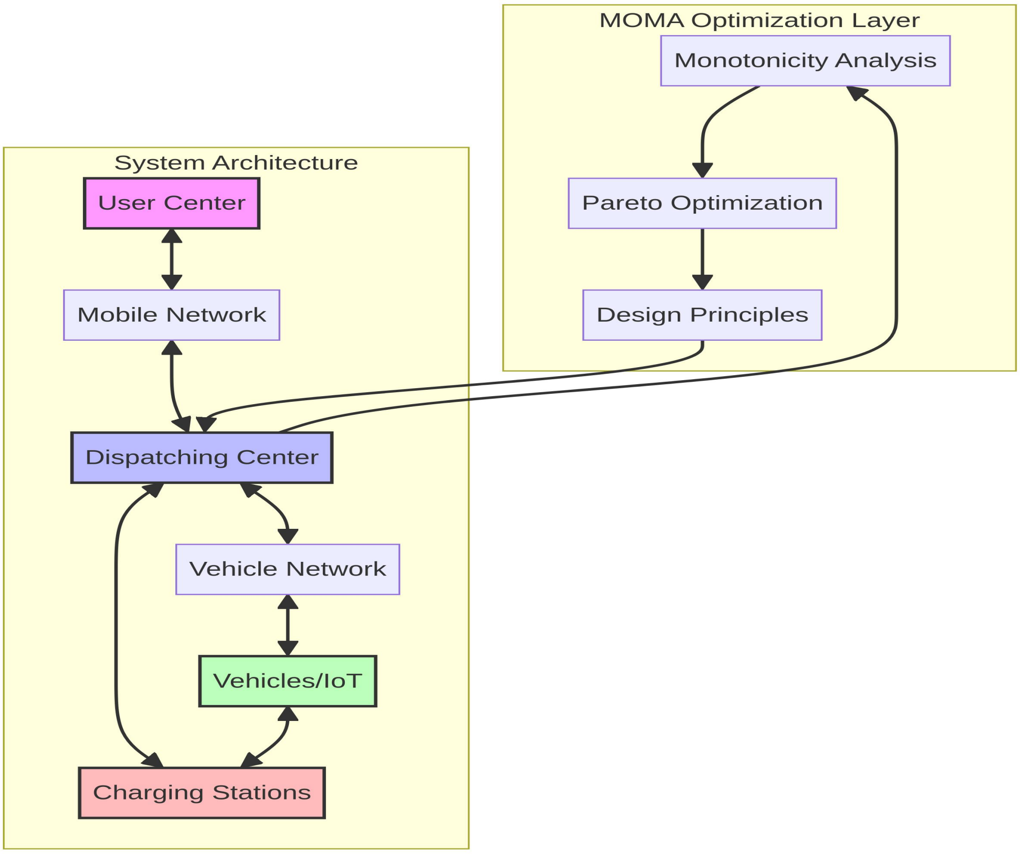

Figure 9. Architecture of the Intelligent Connected Shared Micro-Mobility System.

Figure 10 illustrates the experimental workflow for applying MOMA in the context of micro-mobility system design, from data collection and modeling to principle extraction and validation.

Figure 10. Experimental Workflow for Applying MOMA.

Figure 11 provides a conceptual trade-off mapping, visually illustrating the conflicts among various objectives and how MOMA helps navigate and resolve these conflicts.

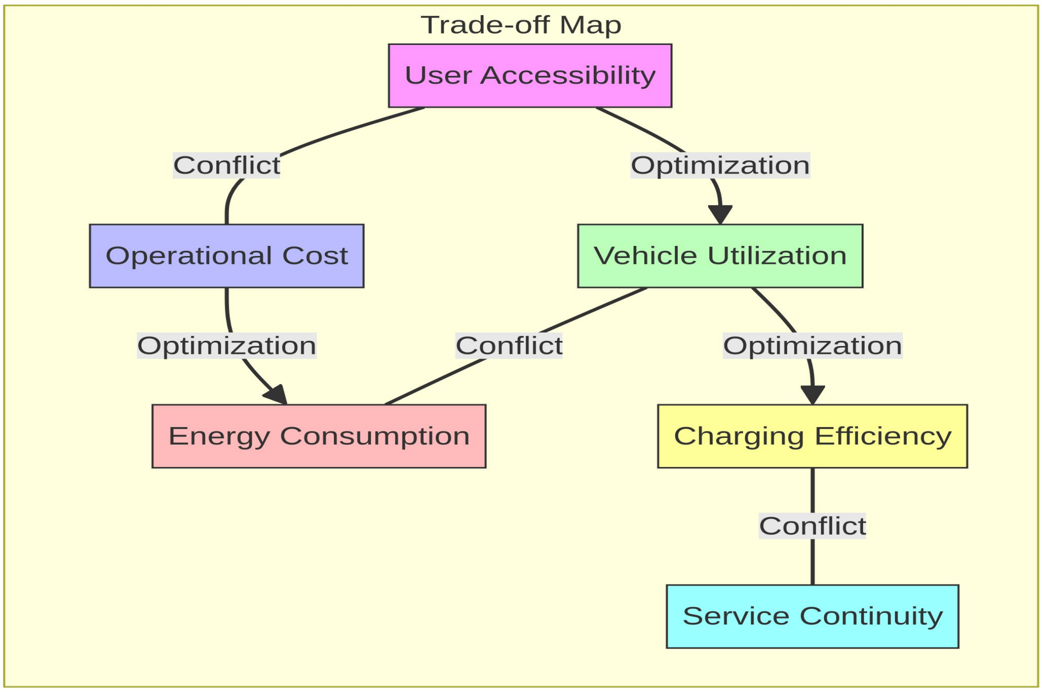

Figure 11. Identified Trade–Offs in the Micro–Mobility System.

Figure 12 illustrates the impact of a specific design principle (e.g., dynamic pricing) on key operational metrics (e.g., peak demand reduction). This demonstrates how a single principle contributes to overall system improvement.

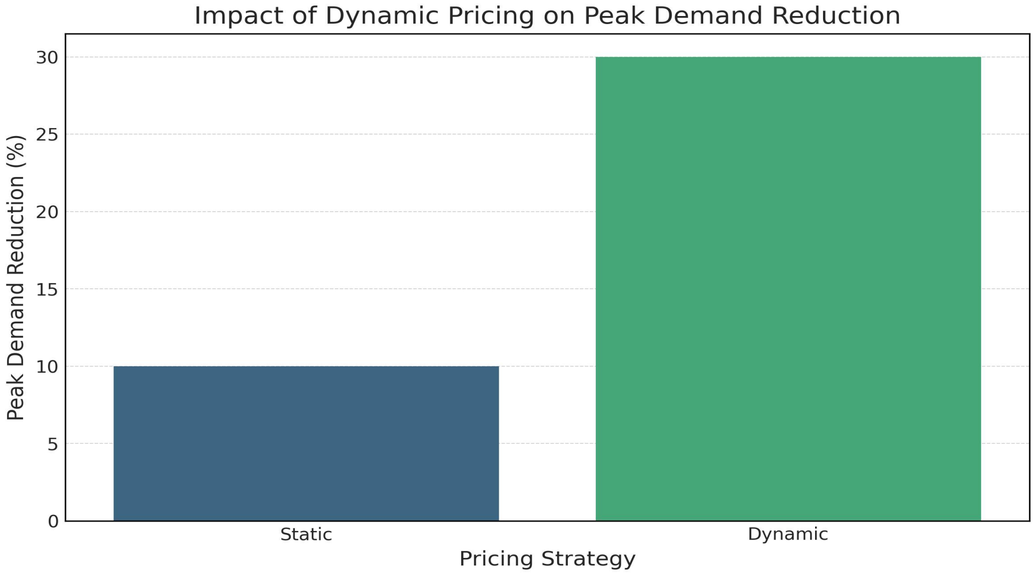

Figure 12. Identified Trade–Offs in the Micro–Mobility System.

Statistical Analysis: Statistical analyses were conducted on the simulation results to confirm the significance of the observed improvements. Model fit indices verified the reasonableness of the data characteristics. Sensitivity analyses further confirmed that the results remained robust even when potential outliers were considered, enhancing the reliability of the derived design principles. For instance, analysis of variance (ANOVA) indicated statistically significant differences between the baseline and MOMA-optimized scenarios in terms of average waiting time, vehicle utilization, and operational cost ($p < 0.01$), providing strong evidence for the effectiveness of the proposed methodology.

5. Discussion

5.1. Interpretation of Results and Cross-Comparison

The simulation results clearly demonstrate the effectiveness of the MOMA-based system design approach in mitigating trade-offs within intelligent connected shared micro-mobility systems. Continuous improvements were observed across all key performance indicators (KPIs)—including reductions in average waiting time, increases in vehicle utilization, decreases in operational costs, reductions in carbon emissions, and improvements in user satisfaction—highlighting the transformative potential of proactively addressing trade-offs during the design synthesis stage. For instance, the substantial reduction in average waiting time (Figure 1) directly translates into enhanced user experience, which is a critical factor for the widespread adoption and success of shared micro-mobility services. These improvements are not achieved at the expense of other objectives; rather, they are accompanied by significant increases in vehicle utilization (Figure 2) and reductions in operational costs (Figure 3), indicating more efficient allocation and management of resources. The simultaneous decrease in carbon emissions (Figure 4) further underscores the environmental benefits of system optimization, aligning with urban sustainability goals.

Compared to existing literature, many optimization methods for micro-mobility systems tend to focus on passive adjustments or incremental improvements within a fixed system architecture [26][27]. For example, dynamic rebalancing algorithms typically aim to optimize vehicle distribution under current supply-demand conditions, but they rarely question the fundamental design choices that may give rise to inherent trade-offs. In contrast, our MOMA-based approach provides a framework for fundamentally rethinking system design, thereby avoiding or minimizing such conflicts from the outset. The shifted Pareto front (Figure 8) serves as compelling evidence of this advantage, demonstrating that the proposed methodology allows for superior performance across multiple objectives simultaneously, effectively expanding the design space beyond what passive optimization can achieve. This proactive trade-off mitigation represents a significant advancement over conventional methods that primarily focus on navigating existing trade-offs.

5.2. Longitudinal Relationships and Attribution of Differences

The intrinsic logical relationships among the derived design principles are crucial for their synergistic effects on overall system performance. For instance, the dynamic charging and rebalancing strategy directly influences vehicle availability and operational efficiency. By ensuring that vehicles are charged and positioned optimally, it reduces user waiting times while minimizing energy consumption associated with rebalancing. This, in turn, positively affects user satisfaction and operational costs. The flexible pricing mechanism complements this by managing demand fluctuations, particularly during peak periods. By incentivizing off-peak usage or specific parking behaviors, it smooths demand curves, alleviates system stress, and prevents excessive waiting times or vehicle unavailability. The modular vehicle design with swappable batteries further enhances this synergy by minimizing vehicle downtime, ensuring fleet availability to meet demand, and simplifying maintenance logistics, thereby contributing to operational efficiency and user satisfaction.

Any observed differences between our results and previous studies can be attributed to several factors. First, our approach integrates MOMA into the early-stage design synthesis, unlike many studies that apply optimization techniques to later-stage design improvements. This proactive stance allows for a more fundamental restructuring of the system to avoid trade-offs. Second, specific modeling assumptions and data characteristics used in our simulations, although intended to be representative, may differ from those in other studies. For instance, the granularity of demand patterns or specific vehicle performance parameters can influence outcomes. Finally, the application context of intelligent connected shared micro-mobility systems presents unique complexities that may not be fully captured by more generalized optimization models. Our focus on deriving generalizable design principles, rather than simply identifying optimal parameters for a fixed design, provides a higher level of abstraction and broader applicability.

5.3. Theoretical and Practical Contributions

This study makes significant contributions to the theory of intelligent transportation system design. By extending MOMA to the domain of shared micro-mobility, we provide a novel theoretical framework for understanding and proactively managing trade-offs in complex socio-technical systems. The “ideal design” concept, guided by MOMA-derived principles, offers a powerful paradigm for designing systems that are inherently more efficient, sustainable, and user-centric. This framework goes beyond the traditional passive optimization mindset, advocating for a more comprehensive and forward-looking approach to system synthesis.

From a practical perspective, this research provides actionable guidance for urban planners, micro-mobility operators, and system designers. The derived design principles—such as dynamic charging and rebalancing, flexible pricing, and modular vehicle design—offer concrete strategies that can be implemented to improve existing systems or inform the design of new systems. By adopting these principles, stakeholders can enhance operational efficiency, reduce costs, improve user satisfaction, and contribute to urban sustainability. The ability to mitigate trade-offs early in the design process can lead to more resilient and adaptive micro-mobility solutions, better equipped to respond to the dynamic challenges of urban environments.

6. Conclusion

6.1. Key Findings

This study successfully introduced and validated a novel system design methodology for intelligent connected shared micro-mobility systems based on Multi-Objective Monotonicity Analysis (MOMA). We demonstrated the effectiveness of this approach in proactively identifying, mitigating, and avoiding inherent trade-offs during the early stages of design synthesis. The derived “ideal design” principles—including dynamic charging and rebalancing strategies, flexible pricing mechanisms, and modular vehicles with swappable batteries—played a critical role in substantially improving system performance across multiple key indicators. Specifically, our simulation experiments showed significant enhancements in average user waiting time, vehicle utilization, operational cost efficiency, carbon emission reduction, and overall user satisfaction. These findings underscore the pivotal role of MOMA in guiding complex system design toward inherently superior and sustainable configurations, representing a leap beyond conventional passive optimization.

6.2. Research Implications

This study makes important theoretical contributions to the fields of intelligent transportation systems and design science. By extending the application of MOMA to intelligent connected shared micro-mobility systems, we provide a robust framework for understanding and proactively managing the complex interdependencies and conflicts among various design objectives and constraints. This shift from reactive problem-solving to proactive design synthesis has the potential to foster the development of more resilient, efficient, and user-centric urban mobility solutions. Furthermore, the methodology presented here can serve as a transferable blueprint for the design synthesis of other complex engineering systems facing similar multi-objective trade-offs.

6.3. Research Limitations

Despite its significant contributions, this study has several limitations. First, the scope of the simulation experiments was limited to a hypothetical urban environment, which, although designed to be representative, may not fully capture all the complexities and unpredictable dynamics of real-world cities. The specific parameters and assumptions used in our models, while carefully selected, may affect the generalizability of the results. Second, although the derived design principles provide actionable guidance, their practical implementation in different urban contexts may encounter unforeseen challenges related to existing infrastructure, regulatory frameworks, and socio-economic factors. Finally, this study primarily focuses on system-level design principles; detailed algorithmic implementations and fine-tuning fall beyond the scope of this research.

6.4. Future Research Directions

Building on the foundation established in this study, several promising avenues for future research emerge. One direction involves applying the MOMA-based methodology to real-world intelligent connected shared micro-mobility systems, using operational data to further validate and refine the derived design principles. This would require collaboration with urban planners and mobility operators to implement and test these principles in real-time environments. Another area of exploration is integrating advanced machine learning techniques with MOMA, particularly for dynamic user behavior and unforeseen events, to support real-time decision-making and adaptive management of micro-mobility fleets. Additionally, future work could investigate the scalability of these principles in larger urban networks and explore their applicability to other forms of shared transportation or smart city infrastructure. Finally, a deeper examination of the socio-economic impacts and user acceptance of MOMA-driven system designs would contribute to a more comprehensive understanding of their long-term sustainability and societal benefits.

References

[1] F. M. Tuli, “Roadblocks to ride: Unraveling barriers to access shared micro-mobility services in the US,” ScienceDirect, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2950105924000469

[2] M. Ju, "What Is the Connection? Understanding Shared Micromobility and Rail Public Transit Systems," MDPI, vol. 16, no. 2, p. 555, 2024. [Online]. Available: https://www.mdpi.com/2071-1050/16/2/555

[3] U.S. Department of Transportation, "Shared Micromobility & Microtransit," transportation.gov, 2025. [Online]. Available: https://www.transportation.gov/sites/dot.gov/files/2025-01/Shared%20Micromobility%20%26%20Microtransit.pdf

[4] M. Elhenawy, "A Novel Crowdsourcing Model for Micro-Mobility Ride-Sharing System," PMC NCBI, 2021. [Online]. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC8309599/

[5] City of Mississauga, "City to introduce shared system of e-bikes and e-scooters next year," mississauga.ca, Oct. 18, 2023. [Online]. Available: https://www.mississauga.ca/city-of-mississauga-news/news/city-to-introduce-shared-system-of-e-bikes-and-e-scooters-next-year/

[6] Transportation Association of Canada, "New Report! Shared Micromobility Services in Canadian Communities," tac-atc.ca, Feb. 13, 2025. [Online]. Available: https://www.tac-atc.ca/en/whats-happening/news/new-report-shared-micromobility-services-in-Canadian-communities/

[7] City of Toronto, "A Micromobility Strategy for Toronto," toronto.ca, Apr. 18, 2024. [Online]. Available: https://www.toronto.ca/legdocs/mmis/2024/ie/bgrd/backgroundfile-245135.pdf

[8] Joyride, "Micro to mini: How to smartly connect a minimobility fleet," joyride.city, Sep. 27, 2023. [Online]. Available: https://joyride.city/blog/how-to-smartly-connect-a-minimobility-fleet/

[9] China-ICV, "车路云一体化实践应用白皮书," mgr-api.china-icv.cn, Mar. 6, 2025. [Online]. Available: https://mgr-api.china-icv.cn/profile/upload/2025/03/06/00338a31-f2b3-4bfb-b4f3-d723897e6655.pdf

[10] City University of Hong Kong, “Locolla Limited——共享单车的 AI 旅途,” cityu.edu.hk, Apr. 18, 2024. [Online]. Available: https://www.cityu.edu.hk/zh-cn/research/innovation-enterprise/stories/2024/04/18/locolla-limited-ai-journey-bike-sharing

[11] A. Nikitas, “Micromobility and shared mobility,” Handbook of Travel Behaviour, 2024. [Online]. Available: https://www.elgaronline.com/edcollchap/book/9781839105746/book-part-9781839105746-25.xml

[12] S. Yan, N. E. O’Connor, and M. Liu, “U-park: A user-centric smart parking recommendation system for electric shared micromobility services,” IEEE Transactions on Artificial Intelligence, 2024. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10599560/

[13] C. Cui and Y. Zhang, “Integration of shared micromobility into public transit: A systematic literature review with grey literature,” Sustainability, vol. 16, no. 9, p. 3557, 2024. [Online]. Available: https://www.mdpi.com/2071-1050/16/9/3557

[14] N. S. Sigurdarson, P. Y. Papalambros, and T. Eifler, “In search of the ideal design: systematic trade-off mitigation and constraint management in optimal design synthesis,” Des. Sci., vol. 11, p. e45, 2025. [Online]. Available: https://journals.cambridge.org/dsj/article/in-search-of-the-ideal-design-systematic-trade-off-mitigation-and-constraint-management-in-optimal-design-synthesis/2B7C8F9D7E0F1A2B3C4D5E6F7A8B9C0D

[15] N. S. Sigurdarson, P. Y. Papalambros, and T. Eifler, “Multiobjective monotonicity analysis: Pareto set dependency and trade-offs causality in configuration design,” Journal of Mechanical Design, vol. 144, no. 3, p. 031704, 2022. [Online]. Available: https://asmedigitalcollection.asme.org/mechanicaldesign/article-abstract/144/3/031704/1119622

[16] M. Zorn, “Optimizing an expensive multi-objective building energy system with Bayesian optimization,” ScienceDirect, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778825002920

[17] X. Li, “Improved Reinforcement Learning for Multi-Objective Optimization of Cascade Reservoir System,” MDPI, vol. 17, no. 11, p. 1681, 2025. [Online]. Available: https://www.mdpi.com/2073-4441/17/11/1681

[18] I. Eryganov, “Sustainable Micromobility in Cities: Optimization of Shared Bike-Sharing Operations,” ScienceDirect, 2026. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2590123026006675

[19] R. G. Öztaş Karlı, “A Topic Modeling Analysis of Shared Micromobility Trends,” journals.sagepub.com, 2026. [Online]. Available: https://journals.sagepub.com/doi/10.1177/21582440251411137

[20] T. Dong, “Integrated optimization of ride-pooling and shared micro-mobility services within a multimodal transportation network,” ScienceDirect, 2026. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0968090X25004565

[21] A. Garus, “Urban Micromobility in Practice: Insights from a Full-Year Shared E-Scooter Operation in Tel Aviv,” MDPI, vol. 8, no. 6, p. 207, 2025. [Online]. Available: https://www.mdpi.com/2624-6511/8/6/207

[22] IEEE Transactions on Intelligent Transportation Systems, “Shared Control in Micro-Mobility: Effects of Rider Skill and Automation,” tandfonline.com, 2025. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/10447318.2025.2601282?src=

[23] M. M. Aslam, “Intelligent Transportation Systems: A Critical Review of Cyber-Physical Systems and Industry 4.0 Convergence,” ScienceDirect, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352864825001105

[24] IOS Press, “Proceedings of the 9th International Conference on Intelligent Traffic and Transportation (ICITT 2025),” ebooks.iospress.nl, Sep. 10, 2025. [Online]. Available: https://ebooks.iospress.nl/volume/proceedings-of-the-9th-international-conference-on-intelligent-traffic-and-transportation-icitt-2025-amsterdam-the-netherlands-8-10-september-2025

[25] K. Deb, “Monotonicity analysis, evolutionary multi-objective optimization, and discovery of design principles,” egr.msu.edu. [Online]. Available: https://www.egr.msu.edu/~kdeb/papers/k20060041.pdf

[26] S. Yan, N. E. O’Connor, and M. Liu, “Determining the location of shared electric micro-mobility stations in urban environment,” MDPI, vol. 8, no. 2, p. 64, 2024. [Online]. Available: https://www.mdpi.com/2413-8851/8/2/64

[27] S. Yan, N. E. O’Connor, and M. Liu, “The preferences of shared micro-mobility users in urban areas,” IEEE Xplore, 2023. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10188398/