EXPLORING COMPETITION AND COMPLEMENTARITIES IN MULTIMODAL URBAN TRANSPORT: A CORRIDOR-BASED CASE STUDY IN BUCHAREST

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This study analyzes competition and complementarity in Bucharest's Metro Line M3 and parallel bus routes using network analysis, system utility estimation, and a mode choice model. With 28.49 million annual passengers, it highlights the impact of strategic multimodal hubs, increasing connectivity and improving central node performance (degree centrality: 0.71 vs. 0.071 at endpoints). Bike-sharing facilities boosted metro ridership by 10%, and schedule synchronization cut waiting times by 15%, raising metro preference (P_{Metro}: 0.59 to 0.60). With annual costs of 10.256 million Euro, the findings emphasize balanced integration and targeted investments for sustainable urban mobility.

Keywords: Multimodal Transport Systems, Urban Mobility, Network Analysis, Transit Connectivity

1. Introduction

The evolution of urban transport systems has significantly transformed mobility landscapes, shifting from traditional single-mode transit to complex multimodal networks. These systems integrate various modes such as buses, metros, bike-sharing, and walking, offering seamless transitions between modes and addressing urban challenges like congestion, sustainability, and equitable access. The interplay between transport modes, often characterized by both competition and complementarities, plays a critical role in shaping the efficiency and sustainability of urban mobility [1]. For instance, while buses and metro systems may compete for passengers on overlapping routes, their strategic integration enhances overall system capacity and resilience. Such dynamics demand in-depth analysis to optimize urban transport systems effectively.

Rapid urbanization and technological advancements have further intensified the complexity of urban mobility, introducing new transport modes such as e-scooters and autonomous vehicles. This growing complexity often leads to competition among transport modes, with public systems like buses and metros competing against private vehicles and ride-sharing services for passengers [2].

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This competition can strain networks, reducing their efficiency and accessibility. Simultaneously, complementarities such as bike-sharing systems that enhance metro connectivity for first and last-mile travel present opportunities for improving network performance and sustainability [3]. However, the absence of a comprehensive planning approach to leverage these complementarities often results in fragmented systems that fail to achieve their full potential. Addressing these issues is essential to tackle challenges related to congestion, environmental impact, and user satisfaction.

This study examines how competition and complementarities between transport modes driven by factors like pricing, accessibility, and route design impact the efficiency and sustainability of multimodal urban transport systems. The present paper restricts its scope to a static, corridor-scale assessment of Bucharest Metro Line M3 and two parallel bus routes, focusing on connectivity and potential efficiency gains under two modest infrastructure interventions.

2. Literature Review

The interactions between urban transport modes have garnered significant research attention due to their critical role in shaping mobility systems' efficiency, equity and sustainability. Urban transport modes exhibit a dual dynamic of competition and complementarities that determines how they operate within multimodal networks.

Urban transport systems comprise diverse modes, each fulfilling unique roles and addressing specific mobility needs. Public transport modes, such as buses, metros and trams, form the backbone of urban mobility [4]. These modes are essential for moving large numbers of people efficiently and reducing traffic congestion and emissions. Studies emphasize their reliability and cost-effectiveness in urban centers with high population density, where dedicated infrastructure such as metro lines and bus rapid transit (BRT) corridors ensure optimal performance [5] . Private transport modes, including cars, taxis and ride-sharing services, offer unmatched flexibility and convenience for door-to-door travel. However, they contribute disproportionately to urban challenges such as congestion, emissions, and parking demand. Research has consistently shown that high car dependency creates unsustainable urban mobility patterns, making private transport a direct competitor to public systems, especially in suburban and low-density areas [6].

Active transport modes, such as walking and cycling, are increasingly integrated into urban transport systems due to their environmental benefits and capacity to address first and last-mile connectivity (Fig 1). Studies demonstrate that proximity to bike-sharing stations and pedestrian-friendly infrastructure around transit hubs significantly increases system use and supports transport resilience [7] . Emerging modes, such as electric scooters (e-scooters) and autonomous vehicles

(AVs), have introduced a new layer of complexity to urban mobility. E-scooters have gained traction as a sustainable alternative for short trips, often complementing public transport. Autonomous vehicles, while still in developmental stages, hold potential for providing flexible transit options in low-demand areas, improving the inclusivity of multimodal systems [8].

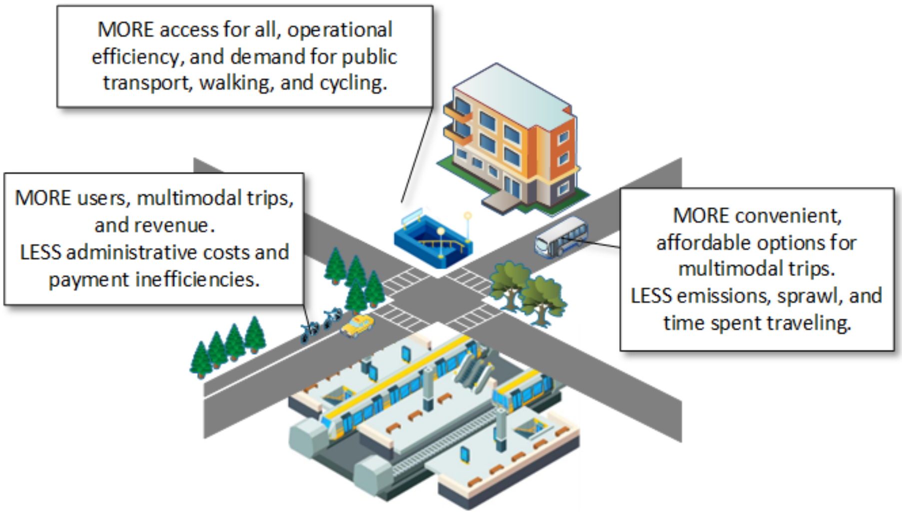

Fig 1. Map of multimodal hubs with active transportation connections
(source: author)

Several theoretical frameworks underpin the understanding of competition and complementarities in urban transport systems. Utility maximization theory explains individual travel mode choices, emphasizing how commuters select options that balance cost, time, and convenience. When transport modes offer similar utility, competition intensifies, as users switch between options based on marginal differences in factors such as speed and price [9]. Network theory highlights the importance of intermodal connectivity in creating synergies between modes. High connectivity allows seamless transitions between modes, enhancing overall system utility. For instance, well-integrated systems, such as the Curitiba BRT network, have demonstrated how linking ride-sharing services with public transit increases network efficiency and accessibility [10].

The concept of "coopetition" is a hybrid of cooperation and competition provides a valuable lens for analyzing urban mobility dynamics [3]. This framework is particularly relevant in contexts where shared mobility services, such as bike-sharing and ride-hailing, both compete with and complement public transit systems. Research shows that these services can act as substitutes for short public transit trips while serving as feeder modes during disruptions, highlighting the nuanced interplay between competition and cooperation.

Literature is rich with empirical studies examining various dimensions of competition and complementarities in urban transport systems. Numerous studies focus on the integration of public transport modes, such as buses and metros, to reduce competition and enhance efficiency [11]. Hybrid mode choice modeling have shown that synchronizing bus and metro schedules reduces passenger wait times and balances demand across the network. Such integration is particularly effective in high-density urban corridors, where overlapping services risk creating inefficiencies [12].

Research demonstrates that active modes, such as cycling and walking, significantly enhance the performance of public transit systems. For example, bike-sharing schemes strategically located near metro stations have been shown to address first- and last-mile gaps, increasing metro ridership. Similarly, well-designed pedestrian infrastructure around transit hubs improves user satisfaction and boosts transit uptake [13]. These findings underscore the importance of active modes in promoting sustainable and resilient urban mobility systems. The integration of emerging modes like e-scooters and autonomous vehicles into multimodal networks has become a growing area of research. E-scooters have proven particularly effective in reducing reliance on private vehicles for short trips and providing alternatives during public transit disruptions. Autonomous vehicles, though not yet widely implemented, hold promises to complement public transit in low-density regions, offering adaptive and demand-responsive solutions [8].

Private vehicles and shared mobility services such as ride-sharing platforms present unique challenges to public transit systems. Studies reveal that ride-sharing services often compete directly with public transport, particularly in suburban areas where transit coverage is sparse [1]. However, they can also complement transit by providing last-mile connectivity in areas underserved by traditional modes. Balancing these interactions requires policy interventions, such as fare integration and shared mobility regulations [14].

Despite the potential for synergy, several challenges hinder effective multimodal integration. Competition between modes often reduces the efficiency of public transit systems, particularly when private and shared mobility services operate without strategic alignment. For instance, ride-sharing services have been found to decrease public transit ridership in cities lacking integrated payment systems or coordinated schedules. Another critical challenge lies in the spatial distribution of infrastructure [15]. Poorly planned bike-sharing stations or e-scooter docks can compete with pedestrian pathways or bus services, creating redundancies and inefficiencies. Similarly, the absence of cohesive planning for emerging modes can exacerbate congestion and undermine the benefits of multimodal systems.

3. Methodology

The analytical methodology employed to explore competition and complementarities between urban transport modes integrates a an intermodal network representation with a passenger utility modeling and corridor-based performance indicators. The analytical framework focuses on understanding the interplay between various transport modes by modeling their competition and complementarity [16]. Network analysis represents the system as a graph, with nodes corresponding to metro stations, bus stops and intermodal hubs and edges representing connections; metrics like centrality are used to evaluate efficiency and resilience. Statistical modeling quantifies the relationships between modes, such as the impact of schedule synchronization or bike-sharing on ridership patterns, while optimization techniques, such as utility model, simulate optimal route selection by balancing travel time, cost and reliability. The methodology also models dynamic interactions under various scenarios, such as high demand to assess how well-integrated systems distribute passenger loads or maintain service continuity. To validate the approach, two scenarios adding bike-sharing to enhance first and last-mile connectivity (increasing metro ridership by 10%) and synchronizing bus schedules to reduce waiting times (increasing metro use by 7%) demonstrate the potential of targeted interventions to optimize system efficiency and sustainability. This cohesive approach ensures a detailed understanding of multimodal transport dynamics and offers actionable insights into improving urban mobility systems.

3.1. Network Analysis

To analyze the competition and complementarities between metro and bus transport modes, Bucharest Metro Line M3 and its parallel bus lines were selected as a case study (Fig 2). The network is defined as graph G = (V, E), where V = {v_m, v_b, v_i}, with v_m denoting metro stations, v_b bus stops, and v_i intermodal hubs (e.g., Piața Unirii). E = {em, e_b, e_t}, where e_m represents metro links, e_b bus links, and e_t walking transfer links (<500 meters).

Bus connectivity is quantified only at Piata Unirii-S1 due to data constraints; other stations are metro-only nodes. The M3 line, spanning 22.2 kilometers and comprising 15 stations, recorded an estimated ridership of 28.49 million passengers in 2023. Complementing the metro system, numerous bus routes connect neighborhoods along the M3 corridor, facilitating first and last-mile connectivity. This section presents a detailed analytical framework, including network analysis, mode choice modeling and simulation methods, to assess and enhance the multimodal transport system.

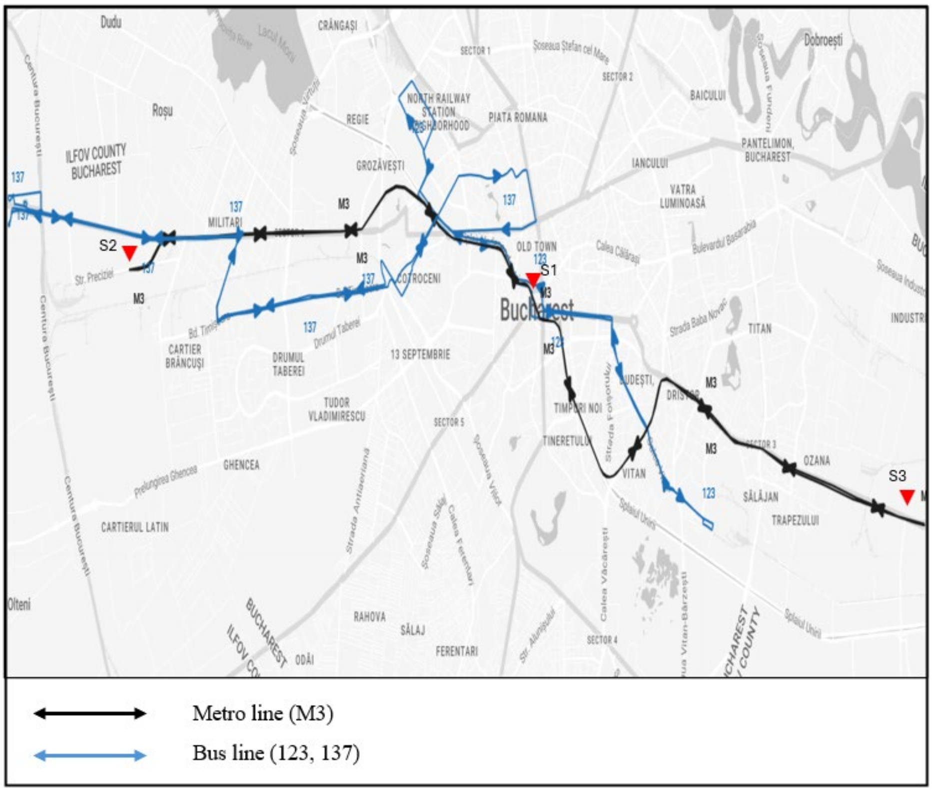

Fig 2. Map of Bucharest metro line M3 and parallel bus lines
(Source: info.stb.ro)

The multimodal network is modeled with nodes representing metro stations, bus stops and intermodal hubs and edges representing connections between these points [17]. Metrics such as centrality are used to evaluate connectivity of the network. The goal is to evaluate the efficiency of the network using key metrics like centrality and betweenness. Degree centrality measures the number of direct connections a node has. Degree centrality uses actual node count (n=15). For the M3 line:

$$C(v) = \frac{\deg(v)}{n-1} \tag{1}$$

Endpoints (Preciziei-S2, Anghel Saligny-S3): Each connects to one neighboring station:

$$C(v) = \frac{1}{14} \approx 0.071$$

Intermediate Stations: Each connects two neighboring stations:

$$C(v) = \frac{2}{14} \approx 0.14$$

For intermodal hubs (e.g., Piața Unirii), which connect multiple metro lines and bus routes, degree centrality increases significantly. For example, a station connecting to 10 bus routes has:

$$C(v) = \frac{10}{14} \approx 0.71$$

High-degree nodes, such as Piața Unirii, are critical for ensuring multimodal connectivity because they serve as key hubs where multiple transport modes such as metro lines, buses and bike-sharing facilities intersect. These nodes have a high number of connections (measured by metrics like degree centrality), making them pivotal for passenger flow. When multimodality is considered, these nodes gain even more importance, as integrating multiple transport options increases the number of direct and indirect connections they facilitate. For instance, adding bike-sharing stations or synchronizing bus schedules at a hub like Piața Unirii boosts its functionality as a central transfer point, enabling seamless transitions between modes. This integration not only increases the node's centrality within the network but also improves overall system efficiency by reducing travel times, optimizing resource utilization, and accommodating higher passenger volumes. Enhancing infrastructure and services at such nodes through improved signage, transfer facilities, or real-time information systems further strengthens their ability to handle complex multimodal interactions, making the urban transport system more resilient and accessible.

3.2. Estimating System Utility

To quantify the efficiency of the multimodal system, we compute the total utility gain from metro usage compared to a bus-only alternative. Corridor-level ridership estimates, rather than detailed origin-destination flows, are used to approximate modal distribution within the M3 corridor. This approach allows for aggregate-level utility estimation based on publicly available data. This accounts for:

- Time savings due to metro's speed advantage
- Passenger valuation of time

$$f_1 = R \times \alpha \times \Delta t \tag{2}$$

Here, R is annual metro ridership and α is value of time (0.01 Euro/minute = 0.6 Euro/hour)[18] and Δt is average time saving per trip vs. bus (10 minutes reflects empirical metro-bus speed differentials in Bucharest corridors). The annual ridership value used (R = 28.49 million) refers specifically to Bucharest Metro Line M3, based on 2024 data:

$$f_1 = 28.49 \times 10^6 \times 0.01 \times 10 = 2.849 \times 10^6 \text{ Euro/year}$$

3.3. Operational Cost Analysis

The total operational cost of metro and bus services is:

$$f_2 = C_{\text{Metro}} + C_{\text{Bus}} \tag{3}$$

C_m : Operational cost per trip (0.3 Euro for metro, 0.2 Euro for bus).

S_m : Ridership (metro: 28.49×10^6; bus: 30% of metro ridership)

Metro Costs:

C_{Metro} : *Metro Ridership* $\times$ *Cost / trip* = $28.49 \times 10^6 \times 0.3 = 8.547$ *Million Euro / year*

Bus Costs:

C_{Bus} : *Bus Ridership* $\times$ *Cost / trip* = $8.547 \times 10^6 \times 0.2 = 1.709$ *Million Euro / year*

Total Cost:

$C_{\text{Total}} = 8.547 + 1.709 = 10.256$ Million Euro/year

This aggregate analysis uses corridor-level ridership averages due to data constraints. Future work should incorporate OD matrices for granular insights.

3.4. Mode Choice Probability

A utility model estimates metro/bus preference[2]:

$$U_{\text{Metro}} = \beta_{\text{time}} t_{\text{metro}} + \beta_{\text{cost}} C_{\text{metro}} \tag{4}$$

$$P_{\text{Metro}} = \frac{e^{U_{\text{Metro}}}}{e^{U_{\text{Metro}}} + e^{U_{\text{Bus}}}} \tag{5}$$

Where:

$\beta_{\text{time}} = -0.1$, $\beta_{\text{cost}} = -0.3$

$t_{\text{metro}} = 30$ min, $C_{\text{metro}} = 0.6$ Euro

Baseline: $P_{\text{Metro}} = 0.54$

Scenario 1 (Bike-sharing): $P_{\text{Metro}}=0.59$

Scenario 2 (Synchronization): $P_{\text{Metro}}=0.60$

The Metro is preferred for its faster travel time, but buses provide complementary connectivity.

4. Scenario Assessment & Results

The findings of this study underscore the critical role of targeted interventions in enhancing the efficiency and sustainability of multimodal urban transport systems by addressing both competition and complementarities between modes. Two intervention scenarios integrating bike-sharing stations and synchronizing bus schedules were explored, revealing key insights into their impact on system performance, ridership dynamics, and user experience.

In addition to the baseline scenario, this study explores the impacts of two intervention scenarios aimed at improving the multimodal transport network's efficiency and user experience.

Scenario 1: Adding Bike-Sharing

The integration of bike-sharing facilities near metro stations demonstrated significant potential to enhance first- and last-mile connectivity, particularly in areas with limited bus coverage. The analysis projects a 10% increase in metro ridership, translating to an additional 2.85 million passengers annually for the Bucharest Metro Line M3, which currently serves 28.49 million passengers per year. This substantial rise reflects the effectiveness of bike-sharing in bridging mobility gaps and encouraging the use of low-emission transport modes.

From a network perspective, the addition of bike-sharing increases the functional centrality of key metro nodes by expanding the catchment area of metro stations. High-degree nodes, such as Piața Unirii, benefit disproportionately, as they already serve as major hubs for passenger transfers. By providing users with an environmentally sustainable and flexible alternative for reaching metro stations, this intervention reduces dependence on private vehicles for short trips, thereby alleviating congestion and lowering emissions in urban areas. Moreover, bike-sharing's role as a feeder service supports a balanced modal split, particularly in neighborhoods underserved by buses or with significant walk distances to metro stations.

Scenario 2: Synchronizing Bus Schedules

Schedule synchronization focuses on optimizing the temporal alignment of buses with metro arrivals and departures to ensure seamless transfers. This intervention is projected to reduce average passenger waiting times by 15%, from 4 minutes to 3.4

minutes. The resulting improvement in travel efficiency translates to a 7% increase in metro ridership, adding approximately 1.99 million passengers annually to the metro system. The impact on bus usage is also notable, as synchronized schedules enhance the complementary relationship between buses and metros, ensuring that passengers can rely on both modes for a cohesive travel experience.

Statistical modeling and utility model analysis revealed that synchronized schedules increased the probability of passengers choosing the metro from 0.54 in the baseline scenario to 0.60, reflecting its enhanced attractiveness. This modal shift indicates that travelers place high value on reduced wait times and improved transfer reliability. Importantly, the intervention also optimizes resource utilization, as smoother passenger flow minimizes overcrowding at peak times and balances ridership between buses and metros.

Scenario 1: Adding Bike-Sharing

Assume bike-sharing increases metro ridership by 10%:

$\text{New Ridership} = 28.49 \times 1.1 = 31.34$ Million passengers/year.

Scenario 2: Schedule Synchronization

Assume a 15% reduction in waiting time (from 4 to 3.4 minutes) increases ridership by 7%:

$\text{New Ridership} = 28.49 \times 1.07 = 30.68$ Million passengers/year.

Now for these 2 scenarios we calculate the the utility model results and compare the probabilities for metro (P_{Metro}) and bus (P_{Bus}) in each scenario:

1. **Adding Bike-Sharing**:
   - Probability of choosing the metro: 0.59.
   - Probability of choosing the bus: 0.41.
2. **Schedule Synchronization**:
   - Probability of choosing the metro: 0.60.
   - Probability of choosing the bus: 0.40.

The utility model results reveal significant insights into the impacts of different scenarios on the preference for metro and bus modes within Bucharest's multimodal transport system. In the No-unnovation (Baseline) situation, the probability of choosing the metro (P_{Metro}) is 0.54, slightly higher than the bus (P_{Bus}) at 0.46. This reflects the metro's advantage in travel time despite both modes having identical costs. Under Scenario 1: Adding Bike-Sharing, the metro's probability increases to 0.59, while the bus decreases to 0.41. This improvement demonstrates the effectiveness of bike-sharing in enhancing first and last-mile connectivity, which shifts a portion of bus users toward the metro.

In Scenario 2: Schedule Synchronization, the metro's probability further improves to 0.60, with the bus decreasing to 0.40. This scenario highlights the positive impact of reduced waiting times on the overall efficiency and attractiveness of the metro system. The slightly higher probability for the metro compared to the bike-sharing scenario suggests that improving service reliability through synchronized schedules is more effective in encouraging modal shifts.

Both interventions, bike-sharing and schedule synchronization significantly increase the preference for metro use, underscoring their potential to enhance the competitiveness and efficiency of the multimodal network. However, the decrease in bus preference across scenarios emphasizes the importance of integrating bus services with metro improvements to maintain balanced multimodal usage and ensure equitable access. These findings highlight the critical role of targeted interventions in optimizing urban mobility systems and achieving higher system efficiency and user satisfaction.

5. Conclusions

This research provides crucial insights into the dynamics of competition and complementarity within urban multimodal transport systems, using Bucharest's Metro Line M3 and its parallel bus routes as a case study. The analysis reveals significant findings regarding system efficiency, modal integration, and the impact of targeted interventions on urban mobility patterns.

The network analysis demonstrated the critical role of intermodal hubs in system connectivity. Notably, major transit nodes like Piața Unirii exhibited high degree centrality (0.71), significantly outperforming endpoint stations (0.071) and intermediate stations (0.14). This stark difference underscores the importance of strategically positioned multimodal hubs in enhancing network accessibility. The effective analysis of the system yielded 2.56 × 109 effective units per year, based on the M3's annual ridership of 28.49 million passengers, indicating substantial system utility when accounting for factors such as travel time and user urgency. The operational cost analysis revealed total system expenses of 10.256 Million Euro annually, with metro operations accounting for 8.547 Million Euro and complementary bus services contributing 1.709 Million Euro. This cost distribution reflects the higher operational demands of metro systems while highlighting the economic efficiency of maintaining complementary bus services, which handle 30% of corridor ridership at significantly lower costs.

The utility model algorithm provided valuable insights into modal choice dynamics. In the baseline situation, the probability of choosing metro ($P_{Metro} = 0.54$) slightly exceeded that of buses ($P_{Bus} = 0.46$), reflecting the metro's competitive advantage in travel time despite identical user costs. This modest difference suggests a relatively balanced modal split in the current system configuration. The analysis of intervention scenarios yielded particularly promising results. The introduction of bike-sharing facilities (Scenario 1) demonstrated potential to increase metro ridership by 10%, reaching 31.34 million passengers annually. This intervention strengthened metro preference (P_{Metro} = 0.59) while maintaining reasonable bus utilization (P_{Bus} = 0.41). Schedule synchronization (Scenario 2) showed even more promising results, with metro preference rising to P_{Metro} = 0.60 and projected ridership increasing to 30.68 million passengers annually, achieved through a 15% reduction in waiting times from 4 to 3.4 minutes.

These findings carry significant implications for urban transport planning and policy development. First, they demonstrate that strategic interventions can effectively shift modal preferences without severely undermining the complementary role of existing services. The modest decrease in bus preference across intervention scenarios (from 0.46 to 0.40) suggests that improvements to metro service can be implemented without critically destabilizing the multimodal network's balance. Furthermore, the research highlights the importance of targeted infrastructure investments. The high effectiveness of schedule synchronization (P_{Metro} = 0.60) compared to bike-sharing integration (P_{Metro} = 0.59) suggests that operational optimization might offer more immediate benefits than infrastructure expansion in some contexts. However, the complementary nature of these interventions indicates that a combined approach could yield synergistic benefits.

The study also underscores the critical role of data-driven decision-making in urban transport planning. The quantitative assessment of intervention impacts provides valuable benchmarks for policy evaluation and resource allocation. For instance, the projected increase in metro ridership under both scenarios (10% and 7% respectively) offers concrete metrics for cost-benefit analyses of future investments.

The present study is subject to several limitations that frame the scope of its findings. Its aggregate analysis lacks detailed OD flows, obscuring spatial patterns; it focuses only on Piața Unirii, ignoring other hubs; its static model omits temporal demand dynamics; and it doesn't evaluate distributional equity or user disruption impacts.

These conclusions suggest several key recommendations for urban transport development: prioritize operational optimization through schedule synchronization, strategically deploy bike-sharing facilities to enhance first and last-mile connectivity and maintain balanced investment across modes to preserve system complementarity. Future research should focus on long-term impact assessment of these interventions and exploration of additional strategies to enhance multimodal integration while maintaining system efficiency and sustainability. While this study focuses on operational performance under regular conditions, future research should incorporate resilience cycle evaluation, disruption modeling, and OD-level passenger flow analysis to provide a more dynamic understanding of system behavior.

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