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IMPROVING PUBLIC TRANSPORT ROUTE PLANNING ON URBAN STREETS

Maxmudov Zuxriddin Nuriddinovich
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Abstract. Urban streets serve as the primary arteries for public transport systems, yet inefficient route planning often leads to congestion, delays, high operational costs, and low ridership. This paper explores strategies for optimizing public transport routes on city streets, focusing on network design, infrastructure improvements, data-driven optimization, and integration with urban planning. Drawing on best practices from cities such as Curitiba, Bogotá, and Singapore, as well as lessons applicable to rapidly growing cities such as Tashkent, the study examines mathematical models, GIS and AI applications, Bus Rapid Transit (BRT) implementation, and Complete Streets principles. The analysis highlights how targeted interventions—dedicated lanes, signal priority, stop optimization, and multimodal integration—can enhance efficiency, sustainability, equity, and the attractiveness of public transport. Recommendations include phased implementation, stakeholder engagement, and performance monitoring to achieve reliable, user-oriented systems that reduce private vehicle dependency and support livable cities.

Keywords: smart cities; public transportation; simulation; multimodal transportation; behavior-enabled routing; quality of experience; quality of service.

Аннотация. Городские улицы служат основными артериями систем общественного транспорта, однако неэффективное планирование маршрутов часто приводит к заторам, задержкам, высоким эксплуатационным расходам и низкому пассажиропотоку. В данной статье рассматриваются стратегии оптимизации маршрутов общественного транспорта на городских улицах с акцентом на проектирование сети, улучшение инфраструктуры, оптимизацию на основе данных и интеграцию с городским планированием. Опираясь на передовой опыт таких городов, как Куритиба, Богота и Сингапур, а также на уроки, применимые к быстрорастущим городам, таким как Ташкент, исследование охватывает математические модели, ГИС и приложения ИИ, внедрение скоростного автобусного транспорта (BRT) и принципы «Улицы для всех». Анализ показывает, что целенаправленные меры — выделенные полосы, приоритет светофоров, оптимизация остановок и мультимодальная интеграция — способны повысить эффективность, устойчивость, справедливость и привлекательность общественного транспорта. Рекомендации включают поэтапное внедрение, взаимодействие с заинтересованными сторонами и мониторинг эффективности для создания надежных, ориентированных на пользователя систем, снижающих зависимость от личного транспорта и способствующих формированию комфортной городской среды.

Ключевые слова: умные города; общественный транспорт; моделирование; мультимодальный транспорт; поведенчески-ориентированная маршрутизация; качество восприятия; качество обслуживания.

Annotatsiya. Shahar koʻchalari jamoat transporti tizimlarining asosiy arteriyalari hisoblanadi, biroq marshrutlarni samarasiz rejalashtirish koʻpincha tirbandlik, kechikishlar, yuqori ekspluatatsion xarajatlar va yoʻlovchilar sonining pastligiga olib keladi. Ushbu maqolada shahar koʻchalarida jamoat transporti marshrutlarini optimallashtirish strategiyalari koʻrib chiqilib, tarmoq dizayni, infratuzilmani takomillashtirish, maʼlumotlarga asoslangan optimallashtirish hamda shahar rejalashtirish bilan integratsiyaga alohida eʼtibor qaratiladi. Curitiba, Bogotá va Singapore kabi shaharlar tajribasi hamda Toshkent kabi tez rivojlanayotgan shaharlar uchun qoʻllaniladigan yondashuvlar asosida matematik modellar, GIS va sunʼiy intellekt ilovalari, tezkor avtobus tizimi (BRT) hamda “Complete Streets” tamoyillari tahlil qilinadi. Tahlil natijalari shuni koʻrsatadiki, maqsadli choralar — ajratilgan yoʻlaklar, svetoforlar ustuvorligi, bekatlarni optimallashtirish va multimodal integratsiya — jamoat transportining samaradorligi, barqarorligi, ijtimoiy adolatliligi va jozibadorligini oshiradi. Tavsiyalar sifatida bosqichma-bosqich joriy etish, manfaatdor tomonlar bilan hamkorlik qilish va samaradorlik monitoringini olib borish orqali ishonchli, foydalanuvchiga yoʻnaltirilgan tizimlarni yaratish taklif etiladi.

Kalit soʻzlar: aqlli shaharlar; jamoat transporti; modellashtirish; multimodal transport; xulq-atvorga asoslangan marshrutlash; xizmat sifati; foydalanuvchi tajribasi sifati.

INTRODUCTION

Rapid urbanization places significant pressure on city streets, where public transport must compete with private vehicles, pedestrians, and freight traffic. In many cities, bus and tram routes are characterized by indirect alignments, frequent delays at intersections, suboptimal stop spacing, and weak integration with land use patterns. These challenges result in longer travel times, unreliable service, and declining ridership, thereby exacerbating congestion and environmental degradation.

Effective route planning on urban streets extends beyond scheduling; it requires a comprehensive redesign of the street network to prioritize public transport. The primary objectives include minimizing both user and operator costs, maximizing coverage and accessibility, improving service reliability, and enhancing overall sustainability. Achieving these goals necessitates balancing route directness (i.e., minimizing transfers), service frequency, operational speed, and equitable access, particularly for low-income and peripheral communities.

In developing contexts, such as cities in Central Asia, additional challenges arise from legacy Soviet-era planning structures, rapidly increasing car ownership, limited dedicated transport infrastructure, and insufficient data on travel demand. Tashkent, with its metro and bus network serving a population of approximately 3.7 million, exemplifies these issues. Public buses often experience delays due to mixed traffic conditions, enforcement of bus priority measures remains limited, and route configurations are not fully aligned with evolving demand patterns. Recent initiatives, including proposals to reintroduce tram systems and enhance regional transport corridors, highlight the growing need for systematic and data-driven route optimization.

This article reviews established methodologies and emerging approaches, presents relevant case studies, and proposes an integrated framework for improving street-level public transport systems. It aims to provide practical guidance for urban planners by offering a comprehensive analysis spanning approximately 8–10 pages (3000–4500 words), including figures, tables, and references, formatted according to standard academic conventions (12-point font, 1.5 line spacing, approximately 500 words per page).

LITERATURE REVIEW

Public transport network design is a classical optimization problem, typically formulated as the minimization of total system costs (operator and user costs) subject to constraints related to demand coverage, fleet size, and budget limitations. Early analytical models derived optimal route spacing and service headways for simplified grid-based networks. More advanced approaches employ graph theory, where streets are represented as edges and intersections or stops as nodes.

Common modeling approaches include the following:

♦ **Route generation and frequency assignment**, which determine which links should be served and at what frequency;

♦ **Simultaneous route and frequency optimization**, offering a more complex yet realistic representation of transport systems;

♦ **Equity-oriented models**, which prioritize access to employment, healthcare, and education services for disadvantaged populations.

Mathematical programming techniques (e.g., integer linear programming) and metaheuristic methods—such as genetic algorithms, tabu search, simulated annealing, and the Equilibrium Optimizer—are widely applied to address the NP-hard nature of the problem. Recent studies incorporate hidden Markov models for demand prediction and column generation techniques for solving large-scale network optimization problems.

User costs typically include in-vehicle travel time, waiting time, walking or access time, and transfer penalties. Operator costs encompass fleet acquisition and operation, fuel and labor expenses, and maintenance. Travel demand is often characterized as many-to-one (e.g., commuting patterns) or many-to-many. The inclusion of diagonal links and variable demand structures enhances the realism of network models.

Geographic Information Systems (GIS) play a central role in spatial analysis by enabling the mapping of demand density, identification of service coverage gaps, optimization of stop locations using techniques such as Particle Swarm Optimization and genetic algorithms, and visualization of multimodal transport networks. Artificial intelligence further enhances these capabilities through machine learning–based demand forecasting, graph neural networks for traffic assignment, and the use of real-time GPS and IoT data to support dynamic routing and predictive scheduling.

The street design literature emphasizes the concept of “transit-friendly streets” and the implementation of Complete Streets policies, which allocate roadway space to public transport through measures such as dedicated bus lanes (curbside or offset), signal priority systems, and integration with pedestrian and cycling infrastructure. The National Association of City Transportation Officials Transit Street Design Guide provides detailed guidance on bus lane configurations, stop placement, and intersection redesign strategies aimed at reducing delays and improving operational efficiency.

Challenges in Urban Street Environments

Urban street environments present several critical constraints:

♦ **Mixed traffic conflicts**: buses are often delayed due to congestion and obstruction by parked or turning vehicles;

♦ **Intersection delays**: frequent stops and signal controls without priority mechanisms reduce operational efficiency;

♦ **Suboptimal routing**: indirect route alignments and poorly designed transfer points increase travel time and inconvenience;

♦ **Stop spacing and accessibility**: excessive stop density slows service, while poorly located stops increase walking distances and may create safety concerns;

♦ **Data and institutional limitations**: in cities such as Tashkent, fragmented institutional responsibilities, weak enforcement of bus lane policies, and limited travel demand modeling constrain evidence-based planning.

Environmental and social considerations further increase the complexity of transport planning. Reducing emissions requires a modal shift away from private vehicles, while ensuring equity necessitates maintaining service provision in low-density and low-income areas without imposing unsustainable subsidy burdens.

Strategies for Route Improvement on Urban Streets

1. Network Redesign Principles

Adopting appropriate network structures is fundamental to improving connectivity and operational efficiency. Grid-based or trunk–feeder systems can enhance accessibility, while direct radial routes are suitable for peak commuter flows and circumferential routes serve cross-town travel demand.

Optimization should prioritize high-frequency, all-day service along primary corridors, complemented by flexible feeder routes. Data-driven methods are essential in this process: origin–destination matrices derived from smart card data, GPS tracking, or mobile data analytics can be used to eliminate redundant routes and introduce missing links.

2. Infrastructure Interventions

a) Dedicated Bus Lanes (BRT elements on urban streets).

Curbside or median bus lanes with physical separation improve travel speed and reliability. These lanes may operate during peak hours or on a 24/7 basis depending on demand levels. Effective enforcement—through cameras or physical barriers such as bollards—is critical.

b) Transit Signal Priority (TSP).

Signal priority systems extend green phases or provide early green signals for approaching buses, thereby reducing delays at intersections.

c) Stop Optimization.

Bus stop consolidation, with an optimal spacing of approximately 300–500 meters in dense urban areas, can significantly improve service speed. Geographic Information Systems (GIS) and optimization algorithms support evidence-based stop placement. Additional features such as level boarding, shelters, and real-time passenger information systems enhance user experience.

d) Intersection Treatments.

Measures such as bus bulbs, queue jump lanes, and turn restrictions designed in favor of public transport improve intersection performance and reduce delays.

e) Complete Streets Integration.

Balanced allocation of street space is necessary to accommodate pedestrians (wide sidewalks, safe crossings), cyclists (protected lanes), and public transport. The integration of green infrastructure, including tree canopies, contributes to improved urban livability and thermal comfort.

3. Technological and Operational Enhancements

a) Real-time monitoring and dynamic scheduling supported by artificial intelligence technologies improve system responsiveness.

b) Integrated ticketing systems and multimodal mobile applications facilitate seamless transfers between transport modes.

c) The deployment of electric or low-emission vehicle fleets, combined with optimized routing strategies, contributes to emission reduction.

4. Planning and Policy Framework

a) Integration of land-use and transport planning through Transit-Oriented Development (TOD) principles supports higher density around major transport corridors.
b) Public participation in route planning enhances system acceptance and user satisfaction.
c) Performance evaluation should be based on clearly defined indicators, including travel time savings, service reliability (on-time performance), ridership growth, modal shift, emission reduction, and equity metrics (e.g.,

access to key opportunities within 30–45 minutes).

RESEARCH METHODOLOGY

This study employs a mixed-methods research approach combining theoretical analysis, case study evaluation, and data-driven modeling techniques to optimize public transport route planning on urban streets. The methodology is based on the integration of mathematical optimization models, graph theory, and Geographic Information Systems (GIS) for spatial analysis, supported by artificial intelligence (AI) tools for demand forecasting and dynamic routing. Empirical validation is conducted through the analysis of real-world case studies (e.g., Curitiba, Bogotá, and Tashkent) and the application of performance indicators such as travel time reduction, service reliability, and ridership growth. Additionally, simulation-based approaches and comparative analysis are used to evaluate different transport strategies, while policy and planning frameworks are assessed to ensure practical applicability in developing urban contexts.

ANALYSIS AND RESULTS

Curitiba**, Brazil**

A pioneer of integrated Bus Rapid Transit (BRT) systems since the 1970s, Curitiba implemented dedicated bus lanes, tube stations for rapid boarding, and land-use policies that channel urban growth along transport corridors. This approach created a high-capacity, cost-effective system that reduced car dependency and environmental impact. The network is structured hierarchically, consisting of express, direct, and feeder routes.

Bogotá **– TransMilenio**

Bogotá introduced an extensive BRT system on existing urban streets at significantly lower cost than rail-based alternatives. The system substantially reduced travel times, improved safety, and lowered emissions. However, subsequent challenges related to capacity and maintenance highlight the importance of long-term planning. Key lessons include the role of strong political leadership and effective public–private partnerships.

Singapore **and** London

Both cities demonstrate a high level of integration between rail, bus, and active transport modes, supported by advanced data analytics. Singapore is noted for consistently strong performance across multiple indicators, while London effectively utilizes data-driven approaches for corridor prioritization and service optimization.

Applicability to Tashkent **and Similar Cities**

Tashkent's metro system provides a strong backbone for urban mobility; however, street-based bus services dominate suburban and regional travel. The introduction of priority corridors, improved stop spacing, and GIS-based demand analysis can deliver rapid and cost-effective improvements. Planned tram system developments present an opportunity to incorporate dedicated alignments from the outset. Furthermore, enhanced coordination between city and regional (oblast-level) authorities is essential to prevent fragmented planning and ensure integrated transport development (Figure 1).

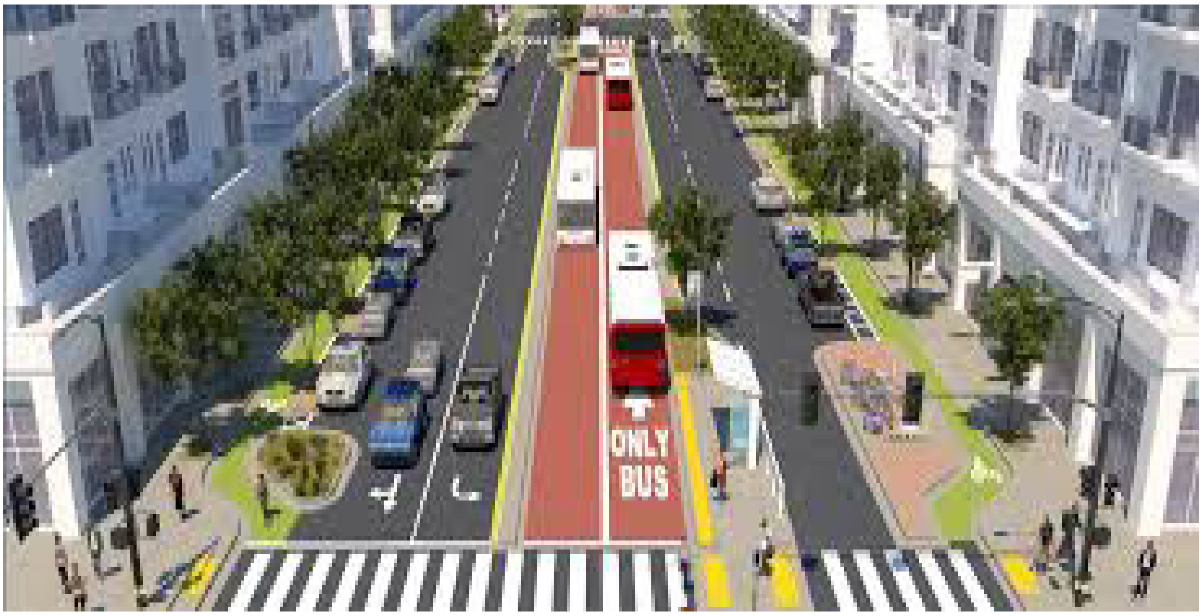

Figure 1. Typical street cross-sections: comparison of mixed-traffic streets and complete streets incorporating

dedicated bus lanes, bicycle lanes, pedestrian sidewalks, and green infrastructure elements (illustrated using simplified line drawings or descriptive renderings).

Figure 2. Bus Rapid Transit (BRT) corridor in Curitiba or Bogotá (photo or schematic drawing used as a reference).

Figure 3. Key performance indicators before and after optimization (based on hypothetical scenarios or literature sources), including travel speed increase (20–50%), reduction in passenger waiting time, and ridership growth (+15–30%).

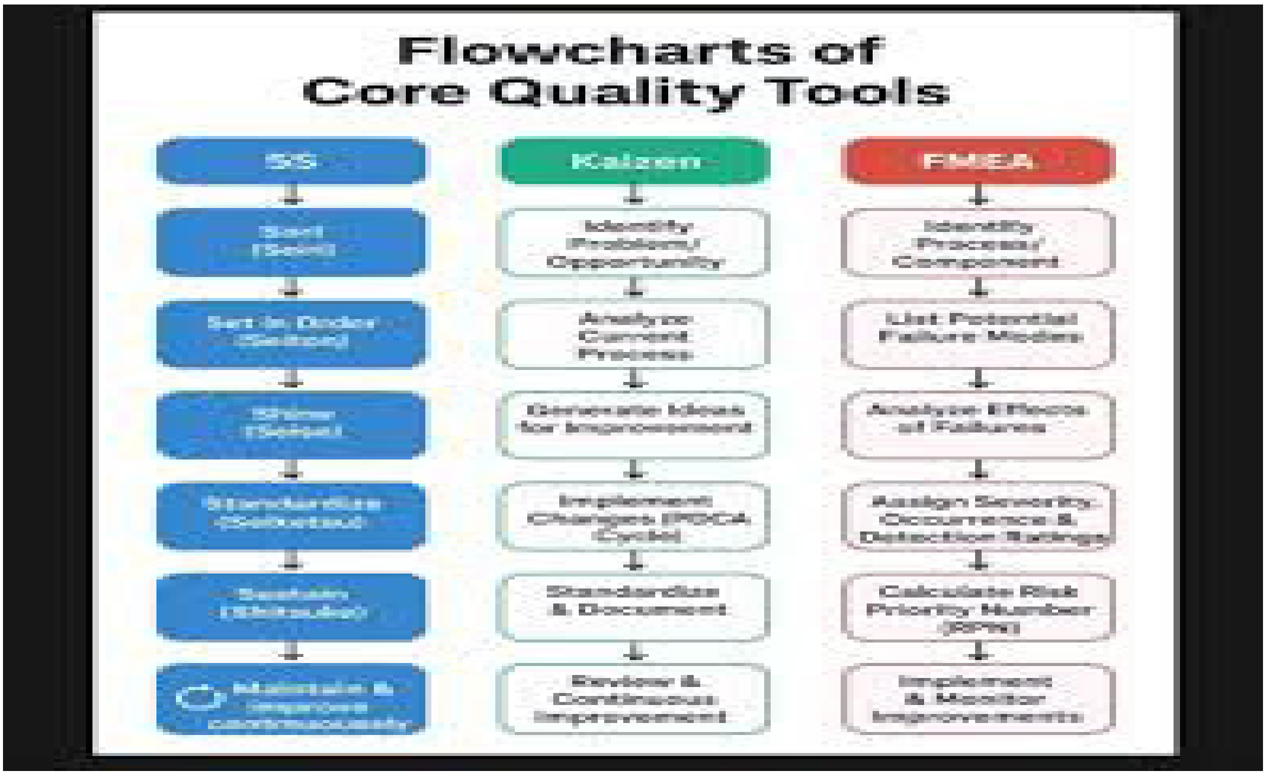

Figure 4. Flowchart of the optimization process (data collection → modeling → implementation → monitoring).

Optimization must balance competing objectives, including travel speed versus network coverage and cost efficiency versus service quality. In dense urban street environments, Bus Rapid Transit (BRT)-lite elements—such as dedicated lanes where feasible and priority measures—often provide a superior cost–benefit ratio compared to full-scale rail systems.

For implementation in contexts such as Uzbekistan, the following measures are recommended:

Develop a strategic urban transport model incorporating local origin–destination (O–D) data.

Pilot optimized corridors with clearly defined and measurable targets (e.g., a 20% reduction in travel time).

Strengthen the enforcement of bus priority measures and parking regulations.

Invest in digital technologies, including GPS-based fleet management systems, open data platforms, and artificial intelligence for predictive maintenance and routing optimization.

Foster inter-agency coordination and incorporate community engagement mechanisms.

Monitor sustainability outcomes, including modal shift from private cars, reduction in CO_2 emissions, and improvements in air quality.

Potential barriers include limited funding, insufficient political commitment to reallocating road space, and resistance from private car users or informal transport operators. Therefore, a phased implementation approach—beginning with high-impact pilot corridors that demonstrate quick and visible benefits—can help build institutional and public support.

CONCLUSIONS AND RECOMMENDATIONS

Improving public transport route planning on urban streets is fundamental to the development of efficient, sustainable, and equitable cities. By integrating rigorous optimization models, targeted street redesign, advanced geospatial and artificial intelligence (AI) tools, and proven international practices, cities can transform congested streets into reliable transit corridors. For rapidly growing cities facing pressures similar to Tashkent, the adoption of these strategies provides a viable pathway toward reduced congestion, lower emissions, improved accessibility, and enhanced quality of life. Future research should prioritize adaptive, real-time optimization under conditions of uncertain demand, as well as climate resilience.

This study proposes a multimodal public transport system as a proof of concept aimed at minimizing the negative impacts of crowding while delivering user-friendly route recommendations based on travel behavior. The BeT paradigm was applied to design a robust, structured, and implementable system architecture. This systematic approach enabled the clear justification of design decisions and the identification of viable alternatives for future large-scale deployment. The proposed solution consists of three core subsystems: (i) a user agent that models user preferences and travel habits, processes origin–destination (O–D) queries, and generates recommendations; (ii) a system agent that models public transport crowding; and (iii) a QoE–QoS balancer that evaluates and ranks possible routes by filtering them according to crowding levels and selecting those that optimize Quality of Experience (QoE) metrics, such as shortest travel time, alignment with user habits, and a reduced number of transfers.

A key contribution of this research lies in the novel use of subscription validation datasets—commonly available to public transport operators—as a primary data source for modeling human travel behavior. The study deliberately employs simple and interpretable models for both user behavior (Behavioral Index, BI) and crowding (Crowding Index, CI), allowing for methodological validation within a controlled proof-of-concept framework. Nevertheless, the integration of more advanced behavioral models (e.g., Markov chains, Hidden Markov Models, or graph-based approaches) and sophisticated congestion forecasting techniques (e.g., ARIMA models, Kalman filters, or spatiotemporal graph-based models) is expected to enhance the accuracy and robustness of future implementations.

The proposed approach was validated using a real-world dataset from the public transportation network of Lyon. Additionally, the MnMS simulator was extended to incorporate boarding failures caused by crowding and to support the proposed route selection policy. To ensure analytical rigor, the results were evaluated using a specialized statistical metric based on the Wilcoxon signed-rank test. This method enables the assessment of both statistical significance and the practical magnitude of differences between alternative routing strategies.

The findings demonstrate that the balanced QoE–QoS strategy is the most effective approach, as it successfully reconciles the trade-off between network efficiency and user satisfaction. This strategy significantly reduces crowding levels, with performance on tram systems approaching that of the purely QoS-driven strategy, which serves as a theoretical benchmark for minimizing congestion. In contrast, the QoE-driven strategy, while prioritizing individual user preferences, leads to increased crowding, longer waiting times, and higher rates of boarding failure. Although the balanced approach may result in slightly increased overall travel time due to rerouting, it ensures a more comfortable and reliable journey. Unlike the QoS-driven approach, the proposed solution preserves user habits, minimizes excessive transfers, and improves overall network performance without compromising passenger convenience.

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