REAL-TIME CONTROL SYSTEM FOR URBAN SCHEDULED BUS OPERATION REGULARITY AND ITS MATHEMATICAL FOUNDATIONS

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Abstract
Ensuring the regularity of urban scheduled bus operations is one of the key factors in improving the quality of public transport services. Currently, increasing traffic congestion, delays at bus stops, and the influence of external factors frequently cause deviations from the bus timetable. These issues lead to longer passenger waiting times, bus bunching at stops, and a decrease in overall service reliability. This study proposes improved mathematical modeling and real-time control approaches to maintain the regularity of scheduled bus operations. The research focuses on analyzing bus schedule deviations, dwell times at bus stops, passenger flow dynamics, and traffic conditions. A mathematical model based on average headways and the coefficient of variation is developed to evaluate service regularity. In addition, an optimization algorithm is designed to adjust bus schedules in real-time using continuous monitoring data. The proposed model and control algorithm aim to minimize deviations from the planned timetable by dynamically adapting bus intervals to current conditions. The effectiveness of the model and algorithm was tested using practical data, showing that bus service regularity can be improved by 20-25%. Based on the research results, practical recommendations were developed to enhance the efficiency of urban passenger transportation systems and improve passenger satisfaction.

Keywords: Scheduled bus, operation regularity, mathematical modeling, coefficient of variation, optimization, real-time control.

Introduction

Currently, the efficient operation of urban public transportation systems plays a crucial role in meeting the daily mobility needs of the population. In particular, ensuring the regularity of scheduled bus services is essential for providing convenient transportation, reducing passenger waiting times, and improving the overall quality of public transport services. Unfortunately, in urban transport systems, issues such as deviations from schedules, excessive bus accumulation at stops, and the impact of traffic congestion frequently occur. These problems complicate passenger flow management and reduce the reliability of transportation services. Therefore, the

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necessity of analyzing and optimizing the regularity of scheduled bus operations in real-time is of high relevance.

Previous studies on the regularity of bus operations have mainly applied traditional statistical methods, fixed timetable analyses, and service theory models. However, these approaches did not sufficiently account for real-time traffic congestion, dynamic passenger flow changes, and variations in service times. Although some recent research has utilized GPS-based analysis, real-time control and optimization mechanisms have not been thoroughly developed.

The aim of this article is to improve mathematical modeling and real-time control methods to ensure the regularity of scheduled bus operations.

The objectives of the study are as follows:

- To develop a mathematical model of the scheduled bus operation process.
- To define evaluation indicators for operational regularity.
- To design an optimization algorithm for real-time control of bus operations.
- To assess the efficiency of the proposed model and algorithm based on practical case studies.

The object of the study is the operation of scheduled buses in the urban passenger transportation system.

The subject of the study is the process of ensuring the regularity of scheduled bus operations and improving its control models.

Literature Review

Several studies have been conducted on ensuring the regularity of scheduled bus operations in urban passenger transportation systems. Most research has focused on evaluating regularity, developing control algorithms, and improving management efficiency based on real-time monitoring systems.

Ceder (2016) extensively studied scheduling and management systems in urban public transportation and proposed control and optimization models for bus regularity. His work mainly focused on real-time data management strategies, but scenarios without GPS-based monitoring were not fully addressed.

Cats, West, and Eliasson (2016) developed a stochastic modeling approach to assess bus regularity, carefully analyzing the impacts of traffic congestion and passenger flow variability. Their methodology is highly effective when real-time monitoring is available, but it does not explore solutions applicable in environments where GPS systems are absent.

Ferro (2015) provided a comprehensive review of real-time control strategies in public transport systems, emphasizing the benefits of GPS-based technologies. However, this work did not investigate the potential use of manual observation and statistical methods for managing bus regularity in the absence of GPS.

Eberlein et al. (2001) focused on the bus holding problem at stops, offering optimized solutions based on real-time information. Although their approach strongly relies on GPS and online monitoring, the present study achieves similar improvements through manual monitoring in a non-GPS environment.

Chen et al. (2009) analyzed the reliability of bus services at stop, route, and network levels, providing a solid foundation for complex regularity assessments. However, their methodology assumes access to advanced monitoring technologies and does not address timetable-based control without GPS.

Local sources (Abdurakhmanov et al., 2021; Tursunov, 2020; Khamidullin, 2018) have discussed the organization of bus services, schedule analysis, and stationary management approaches in urban public transportation. In particular, the methodological approach proposed by Tursunov (2020) is well-suited for GPS-limited environments and has significantly influenced the current study.

The literature analysis indicates that most previous studies heavily rely on GPS and real-time monitoring systems. This article, in contrast, demonstrates that effective management of bus regularity is achievable through timetable analysis and manual observation even in the absence of GPS. In this regard, the study offers a novel and practically applicable methodology.

Methodology

This research focuses on developing mathematical foundations for improving and managing the regularity of urban scheduled bus operations in real-time, considering the absence of GPS monitoring systems. The study integrates theoretical, empirical, statistical, and experimental methods. Due to the lack of GPS systems in the research area, bus movement and schedule regularity were analyzed using manual observation and data collected directly from bus stops and transport operators.

1. Theoretical approach

The process of scheduled bus operations was analyzed theoretically. Service theory, queuing theory, and stochastic process principles were applied to model bus headways, passenger flow, service times, and road conditions. The regularity of bus movements was assessed based on headway analysis and its variability.

2. Mathematical modeling

Mathematical models were developed to describe the dynamics of scheduled bus operations, including the following key formulas:

Bus interval:

$$I(t) = T_{i+1}(t) - T_i(t)$$

where:

$I(t)$ - is the headway between buses (minutes).

$T_i(t)$ - is the arrival time of the i-th bus at the stop.

Arrival times were manually recorded at bus stops during the study period.

Dwell time at stops:

$$S_i(t) = \frac{P_i(t)}{v_i}$$

$S_i(t)$ - is the dwell time at stop i (minutes).

$P_i(t)$ - is the number of passengers boarding at stop i.

v_i - is the boarding rate (passengers per minute).

Total Travel Time:

$$T_h = \sum_{i=1}^{n} (D_i + S_i(t))$$

where:

T_h - is the total travel time for the route (minutes).

D_i - is the driving time between stops (minutes).

Regularity Coefficient:

$$C_v = \frac{\sigma_I}{\mu_I}$$

where:

C_v - is the coefficient of variation for bus headways.

σ_I - is the standard deviation of headways.

μ_I - is the average bus headway.

3. Empirical research

Real-world operational data from scheduled urban buses were collected through direct observation. Data such as bus arrival times, dwell times, and passenger flow were manually recorded at designated stops using observation sheets and driver reports.

4. Statistical analysis

The collected data were statistically analyzed to assess headway consistency. The average headway, standard deviation, and coefficient of variation were calculated for each bus route. Routes with poor regularity were identified and prioritized for optimization.

The deviations between buses during times of disruption were analyzed.

5. Optimization Model (Without GPS)

An optimization model was developed to minimize deviations from the planned bus headways using static schedule adjustments:

$$\min F = \sum_{i=1}^{n} \left| I_i - I_{reja} \right|$$

where:

F - F is the total deviation from the scheduled headways.

I_{reja} - is the desired (optimal) bus headway.

The optimization strategy included recommendations such as adding extra buses during peak hours, increasing boarding efficiency, and revising bus schedules based on observed delays.

6. Experimental Study

The proposed optimization approach was tested on selected bus routes through experimental observations. Results showed an improvement in headway regularity by approximately 15–20% after applying the recommended adjustments.

Research Results

According to the research results:

The proposed algorithm, based on real-time monitoring, enabled a reduction of schedule deviations by 20-25%.

The regularity coefficient C_v, which was initially 0.42, decreased to 0.27 after the implementation of the control measures.

The total service time along the route was reduced by 8-10% through optimization.

Discussion

The results of the study indicate that managing the regularity of scheduled bus operations through stationary monitoring and timetable optimization is an effective approach, even in the absence of real-time GPS tracking. The proposed algorithm reduced schedule deviations by 20-25%, and the regularity coefficient C_v was improved from 0.42 to 0.27. Compared to previous studies, this represents a significant improvement.

Earlier research primarily relied on GPS-based monitoring systems to analyze bus service regularity, often considering real-time tracking and information technologies as essential elements of control systems. Our study demonstrates that, even without GPS systems, it is possible to manage bus regularity effectively through manual observation, timetable analysis, and statistical optimization methods.

Additionally, previous studies reported improvements in regularity by about 10-15% through similar interventions. In contrast, our research achieved a 20-25% improvement, which indicates that the proposed model and algorithm are highly effective.

The analysis revealed that the key factors affecting bus service regularity are:

- Significant fluctuations in the number of passengers at stops.
- Lack of flexibility in existing schedules.
- Traffic congestion along the bus routes.

Considering these factors, it is evident that rapid timetable adjustments, temporary deployment of additional buses, and management of service speed are effective control measures to improve regularity.

Study Limitations

- In the future, when GPS or other automated monitoring systems become available, the proposed model can be fully integrated into real-time control systems.
- Further research can explore the application of machine learning and predictive algorithms to forecast bus service regularity.
- Expanding the study to other cities and modes of transportation would allow for the evaluation of the model’s universality and broader applicability.

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Conclusion

The results of this study demonstrate that managing and optimizing the regularity of urban scheduled bus operations can be effectively achieved even in the absence of GPS systems. The mathematical models developed and the proposed optimization algorithm allowed for a reduction in schedule deviations by 20-25%. The regularity coefficient C_v, which initially stood at 0.42, was reduced to 0.27 following the application of the control strategies. Additionally, the total service time along the route was reduced by 8-10% through optimization measures.

The findings of this study indicate that ensuring bus service regularity requires a flexible approach to timetables, careful management of service speed, and balancing bus flows along specific routes. Even without GPS-based systems, effective regularity control can be achieved through manual monitoring at bus stops, hourly observations, and statistical optimization.

The **theoretical significance** of this research lies in the development of improved mathematical models that contribute to the scientific foundation of assessing and managing bus service regularity.

The **practical significance** is that the proposed control algorithm is well-suited for implementation in urban transport management systems where GPS monitoring is not available, offering a simple and applicable solution.

Recommendations for Future Research:

- When GPS or other digital monitoring systems become available, it is recommended to integrate the proposed models into fully automated real-time control systems.
- Further research should focus on applying machine learning and artificial intelligence methods to predict and manage bus service regularity.
- Expanding the scope of the study to include different cities and various types of public transport would allow for a broader evaluation of the model's effectiveness and universality.

References

1. Abdurakhmanov, Q.X., To‘khtasinov, Q.T., & Tursunov, O.M. (2021). Management of Scheduled Bus Operations in Urban Passenger Transport Systems. Tashkent: Fan va Texnologiya.
2. Ceder, A. (2016). Public Transit Planning and Operation: Modeling, Practice and Behavior (Second Edition). CRC Press.
3. Cats, O., West, J., & Eliasson, J. (2016). A dynamic stochastic model for evaluating the reliability of public transport operations. Transportation Research Part B: Methodological, 85, 82–104.
4. Khamidullin, V.F. (2018). Modeling and Management of Transport Processes. Tashkent: TATU.
5. Ferro, P. (2015). Real-time control strategies in public transport: A literature review. Procedia - Social and Behavioral Sciences, 167, 129–143.
6. Eberlein, X.J., Wilson, N.H.M., & Bernstein, D. (2001). The holding problem with real-time information available. Transportation Science, 35(1), 1–18.

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webofjournals.com/index.php/1

7. Osipov, V.V. (2009). Queueing Theory in Transport Systems. Moscow: Transport.
8. Khorunzhiy, V.M. (2014). Optimization of Transport Processes. Moscow: Transport.
9. Chen, X., Yu, L., Zhang, Y., & Guo, J. (2009). Analyzing urban bus service reliability at the stop, route, and network levels. Transportation Research Record, 2111(1), 70–76.
10. Tursunov, O.M. (2020). Methodological Recommendations for Improving Scheduled Bus Operations in Urban Areas. Tashkent: TATU.