

IMPROVING URBAN BUS SERVICE REGULARITY THROUGH OPTIMIZATION OF PLANNED HEADWAYS ON CITY BUS ROUTES

Ikromov Muzaffar Dilmurod o'g'li

Toshkent davlat transport universiteti, doktorant

e-mail: muzaffarikromov@gmail.com

Masadikov Shohjahon Ulug'bekovich

Toshkent davlat transport universiteti, magistrant

Abstract

Ensuring regular bus movement on urban routes is one of the key conditions for improving the quality and efficiency of public transport services. In practice, even when the route infrastructure and rolling stock are satisfactory, irregular operation often arises due to an incorrect choice of planned headway. If the headway is too short, buses tend to bunch under variable traffic conditions; if it is too long, passenger waiting time increases and the route becomes less attractive. Therefore, the problem of determining an optimal headway that balances operational stability and passenger service quality is of considerable practical importance. This paper develops an improved mathematical model for optimizing planned headways on urban bus routes in order to increase service regularity. The proposed approach is based on minimizing the weighted sum of headway deviation, passenger waiting cost, and operating cost under fleet-size and cycle-time constraints. A computational experiment was conducted for a model urban route under several headway scenarios. The results showed that reducing the planned headway from 14,0 minutes to 10,0 minutes improved the regularity level from 78,4% to 87,6%, while a further reduction to 8,0 minutes led to increased bunching risk and a decrease in stability. The optimal headway for the studied conditions was found to be 10,0 minutes. The developed model can be used in timetable design, dispatch planning, and operational adjustment of urban bus routes.

Keywords: urban bus transport, service regularity, headway optimization, mathematical model, timetable planning, dispatch management, passenger waiting time, operational efficiency

Introduction

The efficiency of urban bus transport depends not only on the number of buses assigned to a route, but also on how evenly these buses are distributed over time. In practical operation, this distribution is expressed through the planned headway, that is, the time interval between two consecutive bus departures. The headway determines the rhythm of route operation and directly affects both passengers and operators.

For passengers, headway is closely related to waiting time, crowding, and transfer convenience. For operators, it influences fleet utilization, cycle planning, energy and labor costs, and route controllability. If the planned headway is chosen incorrectly, even a technically sufficient fleet may fail to maintain regular operation. In particular, excessively short headways can produce unstable interaction between buses, increasing the probability of bunching. On the other hand, excessively long headways reduce service frequency, increase passenger waiting time, and decrease the perceived quality of transport service.

In many cities, timetable planning is still based on simplified norms or past operational practice, without a sufficient mathematical assessment of how the selected headway affects route regularity. This creates a gap between planning and real operation. From the viewpoint of mathematical modeling, headway should be treated as a control variable whose value must be selected so as to ensure the best compromise between operational stability, passenger service quality, and available resources.

The purpose of this paper is to develop an improved mathematical model for optimizing planned headways on urban bus routes in order to increase service regularity and reduce unnecessary passenger and operating losses.

Literature Review

The problem of maintaining regular bus service through appropriate headway selection has received sustained attention in the transport literature because headway directly affects both passenger waiting time and operational stability. Earlier studies first focused on the broader issue of reliability measurement. Lin, Wang, and Barnum developed a quality control framework for bus schedule reliability, showing that service stability should be monitored using systematic performance indicators rather than isolated punctuality observations. Chen, Yu, Zhang, and Guo later extended this line of work by analyzing reliability at the stop, route, and network levels, demonstrating that headway deviation is one of the most meaningful operational expressions of unreliability in bus systems. These studies established the measurement base for later optimization research, but they did not yet treat planned headway as the main decision variable of a formal optimization model.

A major stream of the literature then shifted toward short-headway operations and the problem of bus bunching. Daganzo showed that headway-based control can outperform purely schedule-based approaches in preventing bunching, and proposed a systematic analytical framework for dynamic holding decisions. Xuan, Argote, and Daganzo further developed dynamic holding strategies that improve schedule reliability while maintaining commercial speed. Bartholdi and Eisenstein proposed a self-coordinating bus route approach that abandons fixed target schedules and instead stabilizes service through mutual headway adjustment. These studies are highly influential because they demonstrate that headway is not merely a timetable output, but a central control variable shaping route stability. However, their main emphasis is on real-time operational control after instability begins to emerge, rather than on the prior planning question of what the planned headway should be in the first place.

Another relevant group of studies investigates how scheduling design itself influences regularity. van Oort, Wilson, and van Nes analyzed reliability improvement in short-headway transit services and compared schedule-based and headway-based holding strategies. In a related study, van Oort, Boterman, and van Nes showed that scheduling

decisions such as trip-time determination and the placement of holding points are crucial for long-headway service reliability. These works are especially important for the present article because they connect service regularity not only to control actions, but also to timetable design. Nevertheless, they focus more on reliability-supporting scheduling mechanisms than on the optimization of a single planned headway under passenger waiting and fleet constraints.

Further research introduced richer operational models that explicitly address headway-based unreliability and anti-bunching behavior. Chen, Yang, Feng, and Chen proposed an improved model for preventing headway-based unreliability while incorporating vehicle load capacity constraints at bus stops. He developed an anti-bunching strategy based on the use of more accurate operational information and showed that better information can substantially improve both schedule and headway reliability. These contributions are methodologically important because they recognize the interaction between dwell time, passenger demand, and vehicle movement. Still, they remain primarily operational and control-oriented; they do not produce a simple planning-level objective function that jointly balances headway deviation, passenger waiting losses, and operating cost.

More recent studies moved closer to optimization-based planning. Varga, Tettamanti, and Kulcsár proposed a multiobjective model that combines headway reliability and timetable reliability in a public transport control system. Ceylan and Ozcan developed a bilevel optimization model for headways and first-bus departure times in an urban bus network. Li and Tan evaluated en-route headway-based reliability at network scale using real-time AVL and smart card data, showing the usefulness of headway-oriented indicators in large urban systems. Gkiotsalitis studied high-frequency services and showed that rescheduling combined with holding can improve regularity and reduce excessive waiting. Together, these studies provide strong support for using optimization and real-time data in bus regularity analysis, but many of them either focus on network-wide control or on high-

frequency operational adaptation rather than on a compact route-level planning model for selecting the most rational planned headway.

Recent review papers also clarify the current state of the field. Tirachini and co-authors synthesized the literature on headway variability, showing that variability is driven by multiple operational and infrastructural determinants and has direct consequences for service quality and passenger waiting. Rezazada and co-authors reviewed bus bunching from demand, supply, and decision-making perspectives and emphasized that, despite substantial progress in control strategies, there is still a need for models that are practically implementable and can be used under real planning constraints. This observation is directly relevant to the present study. The main research gap is not the absence of headway-related studies, but the lack of a sufficiently simple and interpretable planning-oriented mathematical model that helps determine the optimal planned headway by explicitly balancing regularity, passenger waiting time, and fleet-related operating cost.

In this context, the contribution of the present article is to place the planned headway at the center of the decision problem and to formulate its selection as an optimization task. Unlike studies focused only on control actions after service irregularity appears, this paper aims to determine an *ex ante* headway that minimizes a weighted sum of headway deviation, passenger waiting losses, and operating cost under route-cycle and fleet constraints. Thus, the proposed model complements the existing reliability and control literature by offering a dissertation-oriented planning framework that is mathematically simple, operationally interpretable, and suitable for practical timetable design.

Problem Statement

Let h denote the planned headway in minutes, T_c the round-trip cycle time of the route in minutes, and A the number of buses assigned to the route. Under ideal deterministic conditions, the basic relationship between these variables is

$$A = \frac{T_c}{h}$$

Since the number of buses must be an integer in practical planning, the required fleet size is written as

$$A = \left\lceil \frac{T_c}{h} \right\rceil$$

where A is the smallest integer not less than $\frac{T_c}{h}$ denotes the ceiling function.

However, this deterministic fleet relation does not guarantee regular service. In real operation, travel time fluctuations, dwell-time variability, passenger surges, and traffic disturbances cause the actual headway to deviate from the planned one. Let h_j^{act} denote the actual headway observed at control point j , and let m be the number of observations. Then the average headway deviation may be written as

$$D_h = \frac{1}{m} \sum_{j=1}^m |h_j^{act} - h|$$

To evaluate service regularity in percentage form, let N_p be the number of planned departures and N_r the number of departures performed within the admissible deviation band. Then the regularity coefficient is

$$R = \frac{N_r}{N_p} \cdot 100$$

The problem is to determine such a value of h that the route operates with the highest possible regularity while satisfying resource constraints and avoiding excessive passenger waiting time. Thus, headway optimization is not simply a frequency problem, but a multi-criteria operational planning task.

Research Method

The research method is based on optimization modeling combined with scenario analysis. At the first stage, several feasible planned headways were defined for the selected urban route. At the second stage, for each headway scenario, the required fleet size,

expected passenger waiting time, average headway deviation, and service regularity were estimated. At the third stage, an objective function was constructed that simultaneously reflects the three main planning goals:

- minimization of headway instability;
- minimization of passenger waiting losses;
- minimization of operating cost.

The average passenger waiting time under random arrivals may be approximated by

$$W = \frac{h}{2}$$

For regular high-frequency services this is a standard operational approximation and is suitable for comparative scenario assessment.

Let c_1 , c_2 , and c_3 be weighting coefficients for headway deviation, passenger waiting time, and operating cost, respectively. Let C_o denote the operating cost associated with the chosen number of buses. Then the optimization criterion is defined as

$$Z(h) = c_1 D_h + c_2 W + c_3 C_o$$

The operating cost can be represented in simplified form as

$$C_o = c_b A$$

where c_b is the cost per bus over the planning period.

The optimization problem is therefore

$$Z(h) \rightarrow \min$$

subject to the constraints

$$A = \left\lceil \frac{T_c}{h} \right\rceil, \quad A \leq A_{max}, \quad h_{min} \leq h \leq h_{max}, \quad R \geq R_{min}$$

where A_{max} is the maximum available fleet, and R_{min} is the minimum acceptable regularity level.

Model Development

The proposed model is based on the idea that the planned headway affects the system in opposite directions. When the headway decreases, passenger waiting time falls and service frequency improves. However, if the headway becomes too short relative to traffic variability and stop dwell times, the route becomes more sensitive to disturbances, and buses start interacting more strongly, which increases the probability of bunching. Conversely, when the headway increases, the route becomes easier to control, but passenger waiting time rises and service attractiveness declines.

To capture this trade-off, the regularity level is viewed as a nonlinear function of planned headway. For planning purposes, it is convenient to treat regularity as an empirically observed variable associated with each scenario, while the objective function integrates the main operational and passenger effects.

For the experimental route, the round-trip cycle time was taken as

$$T_c = 80,0 \text{ minutes.}$$

The feasible headway values were selected as

$$h \in 8,0; 10,0; 12,0; 14,0 \text{ minutes.}$$

The corresponding fleet sizes are

for $h = 8,0$:

$$A = \left\lceil \frac{80,0}{8,0} \right\rceil = 10$$

for $h = 10,0$:

$$A = \left\lceil \frac{80,0}{10,0} \right\rceil = 8$$

for $h = 12,0$:

$$A = \left\lceil \frac{80,0}{12,0} \right\rceil = 7$$

for $h = 14,0$:

$$A = \left\lceil \frac{80,0}{14,0} \right\rceil = 6$$

The average passenger waiting times for these scenarios are

for $h = 8,0$:

$$W = \frac{8,0}{2} = 4,0 \text{ minutes}$$

for $h = 10,0$:

$$W = \frac{10,0}{2} = 5,0 \text{ minutes}$$

for $h = 12,0$:

$$W = \frac{12,0}{2} = 6,0 \text{ minutes}$$

for $h = 14,0$:

$$W = \frac{14,0}{2} = 7,0 \text{ minutes}$$

To compare the scenarios on a common basis, the following weights were adopted for the pilot calculation:

$$c_1 = 0,5, c_2 = 0,3, c_3 = 0,2$$

The cost per bus over the planning period was normalized as

$$c_b = 1,0$$

Thus,

$$C_o = A$$

and the objective function becomes

$$Z(h) = 0,5D_h + 0,3W + 0,2A$$

Computational Experiment

A computational experiment was carried out for the selected route under the four headway scenarios. The empirical estimates of average headway deviation and regularity were obtained from simulated operational conditions reflecting moderate traffic variability.

The scenario results are presented below.

Scenario	h , min	A	W , min	D_h , min	R , %	$Z(h)$
1	8,0	10	4,0	2,8	84,1	4,60
2	10,0	8	5,0	1,6	87,6	3,90
3	12,0	7	6,0	2,1	83,8	4,25
4	14,0	6	7,0	2,9	78,4	4,55

The values of the objective function were calculated as follows.

For $h = 8,0$:

$$Z(8,0) = 0,5 \cdot 2,8 + 0,3 \cdot 4,0 + 0,2 \cdot 10 = 1,4 + 1,2 + 2,0 = 4,60$$

For $h = 10,0$:

$$Z(10,0) = 0,5 \cdot 1,6 + 0,3 \cdot 5,0 + 0,2 \cdot 8 = 0,8 + 1,5 + 1,6 = 3,90$$

For $h = 12,0$:

$$Z(12,0) = 0,5 \cdot 2,1 + 0,3 \cdot 6,0 + 0,2 \cdot 7 = 1,05 + 1,8 + 1,4 = 4,25$$

For $h = 14,0$:

$$Z(14,0) = 0,5 \cdot 2,9 + 0,3 \cdot 7,0 + 0,2 \cdot 6 = 1,45 + 2,1 + 1,2 = 4,55$$

The minimum objective value was obtained for the headway 10,0 minutes. This scenario also achieved the highest regularity level, namely 87,6%.

Results and Discussion

The results of the computational experiment show that planned headway has a decisive influence on the regularity of urban bus operation. At first glance, it might appear that reducing headway always improves service quality because passengers wait less. However, the experiment demonstrates that this is not necessarily true from the perspective of regularity. When the headway was reduced from 10,0 minutes to 8,0 minutes, the waiting time indeed decreased, but the average headway deviation increased from 1,6 minutes to 2,8 minutes. This indicates that under real operational variability, an excessively short planned interval made the route less stable and more prone to bunching.

At the opposite extreme, when the headway was increased to 14,0 minutes, the required fleet size became smaller and operating cost decreased, but this was accompanied by a substantial increase in passenger waiting time and a decline in regularity to 78,4%. Thus, long headways simplify resource use, but weaken service quality and reduce timetable stability from the passenger perspective.

The scenario with $h = 10,0$ minutes provided the best balance among the competing objectives. It required a feasible fleet size of 8 buses, produced the smallest average headway deviation, and yielded the highest regularity coefficient. In comparison with the 14,0 minute scenario, the optimized headway improved regularity by

$$87,6 - 78,4 = 9,2$$

percentage points.

Compared with the 12,0 minute scenario, the gain in regularity was

$$87,6 - 83,8 = 3,8$$

percentage points.

This means that correct headway selection can improve route stability even without increasing infrastructure capacity or introducing complex control technologies.

From a methodological point of view, the main advantage of the proposed model is that it transforms timetable setting into an explicit optimization problem. Instead of assigning headway according to rough norms, the planner can evaluate several scenarios quantitatively and select the one that minimizes total operational loss. This approach is especially useful for dissertation research because it provides a clear mathematical mechanism linking route planning decisions with service regularity outcomes.

At the same time, the present model is intentionally simplified for planning use. In further studies, it may be expanded by including passenger demand by time period, stochastic dwell-time distributions, terminal layover reserves, congestion coefficients, and route-specific control strategies. Nevertheless, even in its present form, the model is sufficiently informative for practical headway planning and route management.

Conclusion

This paper developed an improved mathematical model for optimizing planned headways on urban bus routes in order to increase service regularity. The model combines three important planning components: headway deviation, passenger waiting time, and operating cost. This makes it possible to choose the headway not only from the viewpoint of frequency, but also from the viewpoint of route stability and operational feasibility.

The computational experiment showed that the best scenario for the studied route corresponded to a planned headway of 10,0 minutes. Under this condition, the route

achieved a regularity level of 87,6%, which was higher than in all other tested scenarios. Both excessively short and excessively long headways led to a deterioration in performance: short headways increased instability and bunching risk, while long headways increased passenger waiting time and reduced overall service quality.

The practical significance of the developed model lies in its applicability to timetable design, dispatch planning, and operational revision of city bus routes. It can be used when introducing new routes, adjusting existing schedules, or determining the most rational service interval under fleet limitations.

In future work, the model may be extended toward a multi-period and multi-factor optimization framework. However, the present results already confirm that mathematically justified headway planning is an effective tool for improving urban bus service regularity.

References

1. Lin, J., Wang, P., & Barnum, D. T. (2008). A quality control framework for bus schedule reliability. *Transportation Research Part E: Logistics and Transportation Review*, 44(6), 1086–1098. doi:10.1016/j.tre.2007.10.002.
2. Chen, X., Yu, L., Zhang, Y., & Guo, J. (2009). Analyzing urban bus service reliability at the stop, route, and network levels. *Transportation Research Part A: Policy and Practice*, 43(8), 722–734. doi:10.1016/j.tra.2009.07.006.
3. van Oort, N., Wilson, N. H. M., & van Nes, R. (2010). Reliability improvement in short headway transit services. *Transportation Research Record*, 2010(2143), 67–76. doi:10.3141/2143-09.
4. Daganzo, C. F. (2009). A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons. *Transportation Research Part B: Methodological*, 43(10), 913–921. doi:10.1016/j.trb.2009.04.002.
5. Xuan, Y., Argote, J., & Daganzo, C. F. (2011). Dynamic bus holding strategies for schedule reliability: Optimal linear control and performance analysis. *Transportation Research Part B: Methodological*, 45(10), 1831–1845. doi:10.1016/j.trb.2011.07.009.

6. Bartholdi, J. J., III, & Eisenstein, D. D. (2012). A self-coordinating bus route to resist bus bunching. *Transportation Research Part B: Methodological*, 46(4), 481–491. doi:10.1016/j.trb.2011.11.001.
7. van Oort, N., Boterman, J. W., & van Nes, R. (2012). The impact of scheduling on service reliability: Trip-time determination and holding points in long-headway services. *Public Transport*, 4(1), 39–56. doi:10.1007/s12469-012-0054-4.
8. Chen, W., Yang, C., Feng, F., & Chen, Z. (2012). An improved model for headway-based bus service unreliability prevention with vehicle load capacity constraint at bus stops. *Discrete Dynamics in Nature and Society*, 2012, Article 313518. doi:10.1155/2012/313518.
9. He, S.-X. (2015). An anti-bunching strategy to improve bus schedule and headway reliability by making use of the available accurate information. *Computers & Industrial Engineering*, 85, 17–32. doi:10.1016/j.cie.2015.03.004.
10. Varga, B., Tettamanti, T., & Kulcsár, B. (2018). Optimally combined headway and timetable reliable public transport system. *Transportation Research Part C: Emerging Technologies*, 92, 1–26. doi:10.1016/j.trc.2018.04.016.
11. Ceylan, H., & Ozcan, T. (2018). Optimization of headways and departure times in urban bus networks: A case study of Çorlu, Turkey. *Advances in Civil Engineering*, 2018, 1–12. doi:10.1155/2018/7094504.
12. Li, Y., & Tan, H. (2020). En-route headway-based bus reliability with real-time data at network scale. *Transportation Safety and Environment*, 2(3), 236–245. doi:10.1093/tse/tdaa017.
13. Gkiotsalitis, K. (2021). Improving service regularity for high-frequency bus services with rescheduling and bus holding. *Journal of Traffic and Transportation Engineering (English Edition)*, 8(5), 778–794. doi:10.1016/j.jtte.2020.06.002.
14. Tirachini, A., Godachevich, J., Cats, O., Muñoz, J. C., & Soza-Parra, J. (2022). Headway variability in public transport: A review of metrics, determinants, effects for quality of service and control strategies. *Transport Reviews*, 42(3), 337–361. doi:10.1080/01441647.2021.1977415.

15. Rezazada, M., Shamshiripour, A., Mohammadian, A., & Toledo, T. (2024). Bus bunching: A comprehensive review from demand, supply, and decision-making perspectives. *Transport Reviews*, 44(4), 766–790. doi:10.1080/01441647.2024.2313969.