ASSESSMENT OF THE JOINT EFFECT OF ROUTE LENGTH AND BUS STOP DENSITY ON URBAN BUS SERVICE REGULARITY A DISTANCE- AND STOP-DENSITY-ADJUSTED REGULARITY INDEX FOR TERMEZ BUS ROUTES

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ОЦЕНКА СОВМЕСТНОГО ВЛИЯНИЯ ПРОТЯЖЁННОСТИ МАРШРУТА И ПЛОТНОСТИ АВТОБУСНЫХ ОСТАНОВОК НА РЕГУЛЯРНОСТЬ ГОРОДСКОГО АВТОБУСНОГО СООБЩЕНИЯ ИНДЕКС РЕГУЛЯРНОСТИ АВТОБУСНЫХ МАРШРУТОВ ТЕРМЕЗА С УЧЁТОМ РАССТОЯНИЯ И ПЛОТНОСТИ ОСТАНОВОК

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Abstract. *The study evaluates the joint influence of route length and bus-stop density on urban bus service regularity using route passport and operational data for Routes 1 and 8 in Termez. A distance-corrected regularity coefficient was extended by a stop-density penalty and sensitivity scenarios. Route length, number of stops per kilometre, delay per kilometre, and headway variation were integrated into one index. The calculations show that identical absolute delays generate different operational losses depending on route geometry; higher stop density amplifies dwell-time accumulation, while longer routes increase exposure to disturbances. The proposed index differentiates these effects and supports route-specific timetable and dispatching decisions. The model is suitable for implementation in a GPS/AVL monitoring platform after local calibratio*

Keywords *- bus service regularity; route length; stop density; delay; GPS/AVL.*

Аннотация. В исследовании оценивается совместное влияние протяжённости маршрута и плотности автобусных остановок на регулярность городского автобусного сообщения на основе паспортных и эксплуатационных

данных маршрутов № 1 и № 8 города Термеза. Коэффициент регулярности, скорректированный с учётом протяжённости маршрута, был дополнен поправкой на плотность остановок и сценариями анализа чувствительности. Протяжённость маршрута, количество остановок на один километр, задержка на километр и вариация интервалов движения были объединены в единый индекс. Расчёты показывают, что одинаковые абсолютные задержки приводят к различным эксплуатационным потерям в зависимости от геометрии маршрута; более высокая плотность остановок усиливает накопление времени стоянки, тогда как увеличение протяжённости маршрута повышает подверженность различным нарушениям и задержкам. Предлагаемый индекс позволяет дифференцировать указанные эффекты и поддерживает принятие решений по разработке маршрутных расписаний и диспетчерскому управлению. Модель может быть внедрена в платформу мониторинга GPS/AVL после проведения локальной калибровки.

Ключевые слова: регулярность автобусного сообщения; протяжённость маршрута; плотность остановок; задержка; GPS/AVL

INTRODUCTION

Urban bus service regularity simultaneously characterizes passenger waiting time, service reliability, and the efficiency of rolling-stock utilization. As route length increases, a bus is exposed to more intersections, congested segments, and random disruptions; as stop density increases, deceleration-acceleration cycles and passenger boarding and alighting times accumulate. Therefore, these two parameters should be evaluated through their interaction rather than separately [1]-[3]. [5], [8], [9], [10], [12]

Previous studies have extensively examined real-time delays, headway irregularity, and dwell time. Route length, the number of stops, and the number of intersections have been found to exert significant effects on travel-time reliability [2], [4]. However, the evaluation of routes with different lengths and stop densities by means of one comparable coefficient remains insufficiently developed, particularly under the operating conditions of Termez. [6], [7]

The purpose of this study is to develop an index that quantitatively evaluates the joint effect of route length and bus stop density on urban bus service regularity by combining distance-normalized delay and headway variability, and to test it using Routes 1 and 8 in Termez.

RESEARCH METHOD

The initial data were obtained from the route passports and GPS/AVL observation database compiled for the Termez urban bus network within the dissertation research. The one-way length of Route 1, Airport - Northern Bus Terminal, is 17,7 km and its scheduled travel time is 44 min; Route 8, Termez Bus Terminal - Independence Square, is 8,9 km long and its scheduled travel time is 27 min. In the practical example, delays of 11 and 6 min, respectively, were recorded. [11]

Stop density is defined as the ratio of the number of served stops to route length:

$$D_s = \frac{N_s}{L}, \qquad [D_s] = \text{stops/km} \tag{1}$$

where N_s is the number of served stops, stops, and L is route length, km. The time deviation per kilometre is determined as follows:

$$p_L = \frac{|\Delta t|}{L}, \qquad [p_L] = \text{min/km} \tag{2}$$

The distance-corrected baseline regularity is defined as $K_L = \max(0,1 - p_L / p_0)$. Here, $p_0 = 1$ min/km is the accepted threshold for specific delay. To account for the effect of stop density, a density penalty is introduced:

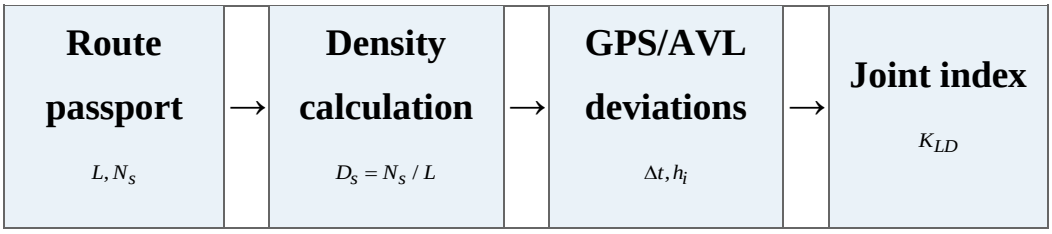
$$P_D = \exp[-\beta \max(0, D_s - D_0)] \tag{3}$$

where $D_0 = 1,20$ stops/km is the baseline density and $\beta = 0,35$ is the scenario coefficient adopted for Termez conditions. The final joint index combines distance-normalized delay, density, and headway variability:

$$K_{LD} = K_L \cdot P_D \cdot (1 - CV_h), \qquad 0 \le K_{LD} \le 1 \tag{4}$$

$CV_h = \sigma_h / \bar{h}$ is the coefficient of variation of actual headways. As the index approaches 0, service irregularity intensifies; as it approaches 1, service becomes more stable. To test the joint marginal effect of the parameters, scenario analysis was conducted for $D_s = 0,8 - 2$ stops/km and $L = 8 - 24$ km.

Figure 1. Algorithm for evaluating the effect of route geometry



Note: all blocks and labels are editable as a Word table.

III. Results and Discussion

A. Baseline Indicators

Table 1

Operational characteristics of the studied routes

Indicator	Route 1	Route 8
Route length, km	17,7	8,9
Scheduled travel time, min	44	27
Observed delay, min	11	6
Specific delay, min/km	0,6215	0,6742
Baseline K_L	0,3785	0,3258

Although the absolute delay is greater on Route 1, distance normalization shows that the disruption is more severe on Route 8. Unlike the conventional regular/irregular binary assessment, this measure incorporates route length into the operational context.

B. Stop-Density Scenario Analysis

Because the final verification of the stop list in the route passports remains open, the joint effect was first assessed using standardized density scenarios. The table values are not observations; they are model results calculated from Equation (4), assuming $CV_h = 0{,}10$.

Table 2

Variation in K_{LD} as stop density increases

D_s, stops/km	Route 1	Route 8

0,8	0,341	0,293
1,0	0,341	0,293
1,2	0,341	0,293
1,4	0,318	0,273
1,6	0,296	0,255
1,8	0,276	0,238
2,0	0,257	0,222

After density exceeds the threshold of 1,2 stops/km, the index decreases consistently on both routes. At 2,0 stops/km, $K_{LD} = 0,257$ for Route 1 and $K_{LD} = 0,221$ for Route 8. Thus, on the shorter route with a stronger baseline distance-related disruption, the additional stop penalty deteriorates regularity more rapidly.

C. Joint Effect and Sensitivity

Route length represents the spatial exposure over which disruptions accumulate, whereas stop density represents the frequency of repeated service processes. Their interaction is linked to the number of stops through $L \times D_s = N_s$. If an average additional variability of $\tau = 0,18$ min occurs at each stop, the expected cumulative stop-related deviation is $\Delta T_s = N_s \tau = L D_s \tau$.

$$\Delta T_s = L D_s \tau \quad \textbf{(5)}$$

Table 3

Expected cumulative deviation by route geometry, min

L, km	$D_s = 1,0$	$D_s = 1,4$	$D_s = 1,8$
8	1,44	2,02	2,59
12	2,16	3,02	3,89
16	2,88	4,03	5,18
20	3,60	5,04	6,48
24	4,32	6,05	7,78

For example, on an 8-km route, when density increases from 1,0 to 1,8 stops/km, the stop-related deviation rises from 1,44 to 2,59 min. On a 24-km route, the

corresponding increase is from 4,32 to 7,78 min. Consequently, simultaneous increases in length and density produce a multiplicative rather than merely additive effect.

D. Graphical Results

Figure 2 shows the decrease in K_{LD} for the two routes as stop density increases. Figure 3 compares cumulative deviations generated by combinations of route length and density under the same CV_h. The graphs are inserted as editable Word charts with editable source data.

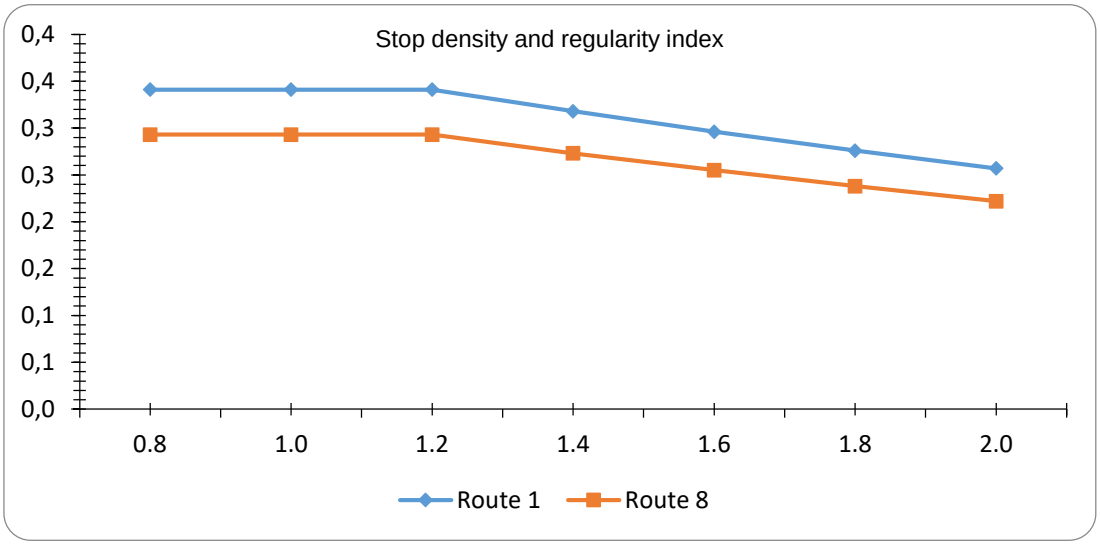


Figure 2. Effect of stop density on the joint regularity index

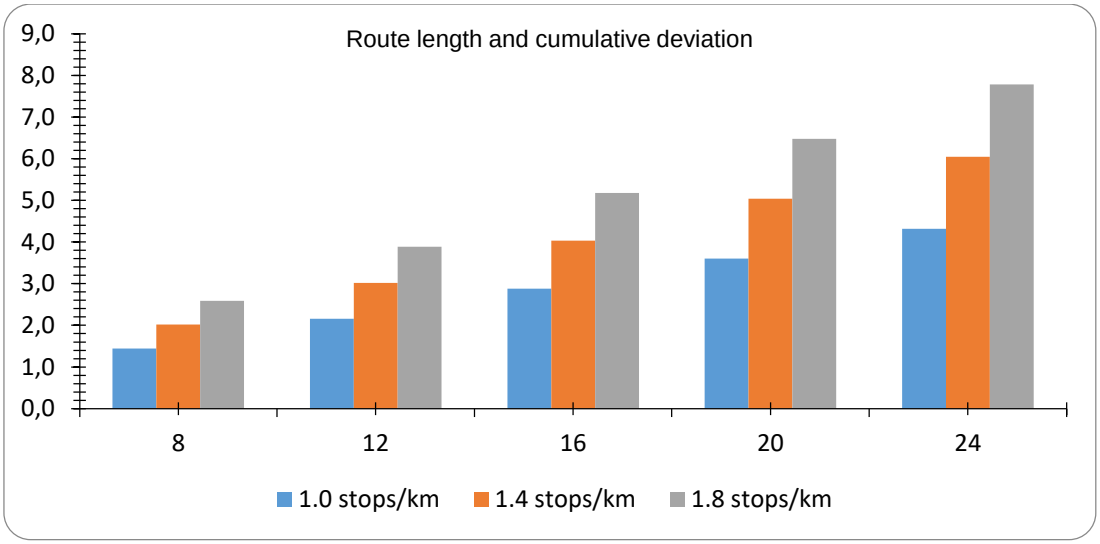


Figure 3. Cumulative deviation by route length and stop density

The results show that route length alone does not determine regularity. On a long route, scheduled recovery time and lower stop density may partially absorb disturbances; on a short but densely stopped route, the relative contribution of each

stop is larger. Therefore, dispatching criteria should be adapted to L, D_s, and CV_h, rather than using one absolute delay threshold for every route.

A practical advantage of the proposed index is that it can be calculated automatically from a GPS/AVL data stream and enables routes to be compared on the same dimensionless scale. When $K_{LD} < 0{,}30$, timetable recalibration, holding, or short-turning is recommended; when $0{,}30 \le K_{LD} < 0{,}60$, headways should be monitored; and when $K_{LD} \ge 0{,}60$, normal control is appropriate. [13], [14], [15]

E. Sensitivity and Formulation of Control Decisions

To test parameter dependence, sensitivity analysis was performed for density-penalty values $\beta = 0{,}20$, 0,35, and 0,50. These values represent low, medium, and high operational sensitivity to increasing stop density. The results calculated for $D_s = 1{,}8$ stops/km and $CV_h = 0{,}10$ are presented in Table 4.

Table 4

Sensitivity of K_{LD} to parameter β

β	**Route 1**	**Route 8**	**Sensitivity level**
0,20	0,302	0,260	low
0,35	0,276	0,238	medium
0,50	0,252	0,217	high

As β increased from 0,20 to 0,50, the Route 1 index decreased from 0,302 to 0,252, while the Route 8 index decreased from 0,260 to 0,217. The ranking of the routes did not change: Route 8 remained less regular in every scenario. This confirms the robustness of the main conclusion to the selected parameter value.

A dispatching decision depends not only on the index value but also on the component responsible for its decrease. If PL is high while D_s is normal, segment travel time or congestion is the primary cause. Conversely, if PL is moderate but D_s is high, stop-service time and deceleration-acceleration cycles dominate. Growth in CV_h indicates uneven spacing between buses and an increased risk of bus bunching.

Table 5

Control measures corresponding to components of K_{LD}

Diagnostic condition	Primary cause	Recommended measure
$p_L > p_0$, $D_s \le D_0$	Segment delay and congestion	Recovery time, signal priority, short-turning
$p_L \le p_0$, $D_s > D_0$	Stop density	Limited-stop service; faster boarding and alighting
$CV_h > 0.20$	Headway variability	Holding, headway control, reserve bus
$K_{LD} < 0.30$	Combined disruption	Timetable recalibration and dispatching intervention

Because Route 1 is longer, control points should be located in its middle and downstream segments. This enables early detection of delays accumulating over the route. On Route 8, the specific delay is higher relative to its short distance; therefore, punctual terminal dispatch and dwell-time control within clusters of densely spaced stops should receive priority.

The proposed calculation sequence operates in three stages within a digital platform. First, L and N_s are obtained from the route passport, while Δt and h_i are obtained from the GPS/AVL stream. Second, D_s, p_L, CV_h, and K_{LD} are calculated. Third, a recommendation is generated for the dispatcher according to the index range and its causal component. Repeated updating allows the decision to reflect the current operational state rather than a static timetable.

A limitation of the model is that the density results reported in this article are based on standardized scenarios. Final operational calibration should incorporate each route's actual stop list, stop type, passenger exchange, number of traffic signals, and peak-period CV_h. Nevertheless, the scenario analysis identifies the direction of the interaction between route length and stop density and reveals critical combinations for operational control.

IV. Conclusion

The K_{LD} index, which jointly accounts for route length and stop density, differentiates the severity of the same absolute delay across bus routes with different geometries. Baseline distance-corrected regularity on Routes 1 and 8 in Termez was 0,3785 and 0,3258, respectively; under the 2,0 stops/km scenario, the index decreased to 0,257 and 0,221. The model shows that when length and density rise simultaneously, the cumulative stop-related deviation intensifies according to $LD_s\tau$. Calibration using actual stop lists, multi-day GPS/AVL observations, and separate peak/off-peak coefficients will support route-specific timetables and dispatching decisions for the Termez bus network.

In practical terms, differential standards reflecting distance and stop density should replace one identical delay threshold for all routes. Control points and intermediate recovery time should be prioritized on long routes, while dwell time and headway variability should be prioritized on densely stopped routes. This approach directs dispatching intervention toward the actual cause and reduces unnecessary holding.

Future research will calibrate the D_0 and β parameters of K_{LD} using actual GPS/AVL and APC observations and test the results across seasons and peak/off-peak periods. A multi-criteria extension that incorporates additional passenger waiting time and energy consumption should also be developed.

References

[1] J. Soza-Parra, J. C. Muñoz, and S. Raveau, “Factors that affect the evolution of headway variability along an urban bus service,” Transportmetrica B: Transport Dynamics, vol. 9, no. 1, pp. 479–490, 2021.

[2] Q. Zhang, Z. Ma, P. Zhang, Y. Ling, and E. Jenelius, “Real-time bus arrival delays analysis using seemingly unrelated regression model,” Transportation, vol. 53, pp. 571–602, 2026, doi: 10.1007/s11116-024-10507-3.

[3] M. A. Esfeh, A. Wirasinghe, and L. Kattan, “Waiting time and headway modeling considering unreliability in public transit service,” Transportation Research Part A: Policy and Practice, vol. 155, pp. 180–199, 2022.

[4] A. Kathuria, M. Parida, and R. S. Chalumuri, “Travel-time variability analysis of bus rapid transit system using GPS data,” Journal of Transportation Engineering, Part A: Systems, vol. 146, no. 6, 05020003, 2020.

[5] T. Zhou, W. Wu, L. Peng, M. Zhang, Z. Li, Y. Xiong, and Y. Bai, “Evaluation of urban bus service reliability on variable time horizons using a hybrid deep learning method,” Reliability Engineering & System Safety, vol. 217, 108090, 2022.

[6] N. Singh and K. Kumar, “A review of bus arrival time prediction using artificial intelligence,” WIREs Data Mining and Knowledge Discovery, vol. 12, no. 4, e1457, 2022.

[7] Z.-Y. Xie, Y.-R. He, C.-C. Chen, Q.-Q. Li, and C.-C. Wu, “Multistep prediction of bus arrival time with the recurrent neural network,” Mathematical Problems in Engineering, vol. 2021, pp. 1–14, 2021.

[8] Y. S. Chung, “Characterizing spatiotemporal patterns of bus bunching using vehicle trajectory data,” Journal of Traffic and Transportation Engineering, vol. 11, 2024.

[9] V. Lukic Vujadinovic et al., “AI-driven approach for enhancing sustainability in urban public transport through headway regularity,” Sustainability, vol. 16, no. 17, 7763, 2024.

[10] A. Ceder, Public Transit Planning and Operation: Modeling, Practice and Behavior, 2nd ed. Boca Raton, FL: CRC Press, 2016.

[11] M. D. Ikromov, “Improving the methodology for determining and evaluating urban scheduled bus service regularity: the case of Termez,” Ph.D. dissertation, Tashkent State Transport University, Tashkent, Uzbekistan, 2026.

[12] Transportation Research Board, Transit Capacity and Quality of Service Manual, 4th ed. Washington, DC: The National Academies Press, 2022.

[13] L. Mertens, B. Amberg, and N. Kliewer, “Integrated bus timetabling and scheduling with a mutation-based evolutionary scheme maximizing headway quality and connections,” Operations Research Forum, vol. 5, art. 25, 2024, doi: 10.1007/s43069-024-00296-x.

[14] X. Zhai, F. Guo, and R. Krishnan, “An online optimal bus signal priority strategy to equalise headway in real-time,” Information, vol. 14, no. 2, art. 101, 2023, doi: 10.3390/info14020101.
[15] S. Liang, R. Leng, H. Zhang, and J. Zhao, “Two-stage transit signal priority control method to improve reliability of bus operation considering stochastic process,” Transportation Research Record, vol. 2677, no. 2, pp. 1713–1727, 2023, doi: 10.1177/03611981221113318.