MODELING BUS STOP DWELL TIME AND ITS EFFECT ON URBAN BUS SERVICE REGULARITY

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Abstract

Bus stop dwell time is one of the main operational factors affecting the regularity of urban bus services. Even when route length, fleet size, and timetable structure are acceptable, irregular operation can emerge because of excessive boarding and alighting time at critical stops. This paper develops an improved mathematical model for assessing the influence of dwell time at bus stops on urban bus service regularity. The proposed approach combines a stop-level dwell time function with a route-level regularity equation. The stop-level function includes passenger boarding, passenger alighting, and stop crowding effects, while the route-level model links cumulative dwell time to the regularity coefficient. A computational experiment was carried out for a model urban route with several demand scenarios. The results showed that an increase in cumulative dwell time from $2,1$ minutes to $5,1$ minutes reduced the expected regularity level from $88,8%$ to $74,8%$. The estimated regularity model $R = 98,67 - 4,68D$ indicates that each additional minute of cumulative dwell time decreases regularity by $4,68$ percentage points. The proposed model can be used in timetable revision, stop-level diagnostics, dispatch control, and route improvement planning.

Keywords: urban bus transport, dwell time, service regularity, bus stop delay, mathematical model, boarding and alighting, stop crowding, operational reliability

Introduction

Urban bus service regularity is determined not only by route length, traffic conditions, and fleet allocation, but also by what happens at the stops. Among stop-level factors, dwell time has special importance because it directly affects vehicle progression, headway stability, and accumulated delay along the route. Recent reviews show that accurate dwell-time estimation is essential for arrival prediction and service reliability analysis, while empirical studies based on APC and AVL data confirm that dwell-time patterns vary strongly across stops and times of day.

In practical operation, excessive dwell time is usually generated by high boarding and alighting volumes, payment delays, platform crowding, or interference near the stop. These factors may appear local, but their cumulative effect can destabilize the full route. Studies on dwell-time determinants, boarding and alighting dynamics, fare-payment effects, and dwell-time variability all indicate that stop-level delay is one of the main sources of bus unreliability.

However, a methodological gap remains. Much of the literature estimates dwell time itself, or studies stop operations in isolation, while fewer works provide a compact mathematical relationship between cumulative dwell time and route-level regularity. For planning and dispatch purposes, transport agencies need a model that answers a simpler operational question: how much regularity is lost when total dwell time increases by one minute. This paper addresses that gap by developing a stop-to-route mathematical framework for evaluating the influence of dwell time on bus service regularity.

Problem Statement

Let d_j denote the dwell time at stop j, and let D denote the cumulative dwell time over the set of critical stops on the route. Then

$$D = \sum_{j=1}^{m} d_j$$

where m is the number of analyzed stops.

Let R denote the route regularity level in percent. The research problem is to determine a mathematically interpretable relationship between the cumulative dwell time D and the route regularity R, while also accounting for the main stop-level causes of dwell time.

In practical transport management, this problem has two levels. At the first level, it is necessary to estimate dwell time at each stop as a function of passenger and operational characteristics. At the second level, it is necessary to assess how the sum of these stop-level dwell times affects the stability of route operation.

Thus, the paper solves two connected tasks:

- to construct a stop-level dwell-time model;
- to develop a route-level regularity model based on cumulative dwell time.

Research Method

The research method is based on a two-stage mathematical modeling approach.

At the first stage, a stop-level dwell-time equation is introduced. Dwell time is treated as a function of passenger boardings, passenger alightings, and stop crowding conditions. The general form is

$$d_j = \alpha + \beta_1 b_j + \beta_2 a_j + \beta_3 c_j$$

where b_j is the number of boarding passengers at stop j, a_j is the number of alighting passengers at stop j, c_j is a crowding or interference factor, α is the fixed service component, and β_1, β_2, β_3 are model coefficients.

At the second stage, the cumulative dwell time is linked to route regularity through a linear explanatory relation

$$R = \theta_0 - \theta_1 D$$

where θ_0 is the intercept and θ_1 is the dwell-time sensitivity coefficient.

The route travel time is also written as

$$T = T_0 + D$$

where T_0 is the running time excluding stop dwell components.

This structure makes it possible to move analytically from passenger activity at individual stops to regularity performance at route level.

Literature Review

The earliest dwell-time studies mainly focused on estimating the service time loss produced by passenger boarding and alighting. Guenther and Sinha modeled bus delay caused by passenger exchange, while Rajbhandari, Chien, and Daniel later used automatic passenger counter information to estimate bus dwell times more systematically. Dueker and co-authors then showed that dwell time is determined not only by passenger activity, but also by lift operations, route type, and other operational effects. These studies established the classical empirical basis of dwell-time modeling.

A second group of studies examined the internal structure of dwell time in more detail. Tirachini showed that different fare collection systems, vehicle floor design, and passenger age composition significantly influence dwell time. Fletcher and El-Geneidy demonstrated that fare payment type and crowding have measurable fine-grained effects on dwell duration. Sun and co-authors advanced the field further by modeling boarding and alighting dynamics directly, while Fernández, Valencia, and Seriani analyzed passenger saturation flow through public transport doors. Together, these studies made it clear that dwell time is not a fixed linear constant, but a process shaped by passenger interaction and stop conditions.

Another important research direction links dwell time to broader service reliability. Ghanim, Dion, and Abu-Lebdeh showed that dwell-time variability affects the performance of transit signal priority, which means that stop delay variability matters not only locally but also for corridor progression. Cats argued for a regularity-driven bus operation philosophy in which operational control should target service evenness rather than only schedule conformance. Arhin and co-authors introduced the broader concept of total bus stop time and showed that minimizing stop-related delay can improve transit reliability. Glick and Figliozzi later emphasized that dwell time is a major contributor to bus travel time variability and that standard estimation approaches may contain biases if stop context is ignored.

Recent studies reinforce the same conclusion. Rashidi, Ataeian, and Ranjitkar reviewed the dwell-time literature and noted that accurate dwell-time estimation is fundamental for reliable arrival prediction and service planning. More recently, Kwesiga, Guin, and Hunter analyzed one year of APC data and showed that dwell time varies strongly by stop and time of day, with larger dwell times typically associated with higher variability. These findings are highly relevant for route-level regularity analysis because they imply that cumulative stop delays cannot be treated as fixed values. At the same time, the literature still contains relatively few compact models that convert cumulative dwell time into a direct regularity-loss coefficient for route management. The present paper is intended to fill that gap.

Model Development

For the present study, the stop-level dwell-time model is specified as

$$d_j = 0,18 + 0,04b_j + 0,025a_j + 0,12c_j$$

where dwell time is measured in minutes, b_j and a_j are passenger counts, and c_j is a binary crowding factor taking value 1 under high platform interference and 0 otherwise.

The interpretation of the coefficients is straightforward. The value 0,18 reflects the base service time at the stop even when passenger exchange is low. Each additional boarding passenger increases dwell time by 0,04 minutes, each additional alighting passenger increases it by 0,025 minutes, and crowding adds 0,12 minutes.

The cumulative dwell time over the critical stops is

$$D = \sum_{j=1}^{m} d_j$$

The total route time is then

$$T = T_0 + D$$

For the computational experiment, the running time without dwell losses is taken as

$T_0 = 28,0$ minutes.

Based on scenario calculations, the route-level regularity equation is estimated as

$$R = 98,67 - 4,68D$$

This means that each additional minute of cumulative dwell time reduces route regularity by 4,68 percentage points. This coefficient is the central analytical result of the model.

To illustrate the stop-level formula, consider a critical stop with $b = 9$, $a = 5$, $c = 1$

Then the predicted dwell time is

$$d = 0,18 + 0,04 \cdot 9 + 0,025 \cdot 5 + 0,12 \cdot 1$$

$d = 0,18 + 0,36 + 0,125 + 0,12 = 0,785$ minutes.

Thus, one high-demand crowded stop may consume almost $0,8$ minutes of dwell time, which becomes substantial when several such stops occur on the same route.

Computational Experiment

The computational experiment was performed for a model urban route with four critical stops and a planned headway of $10,0$ minutes. Instead of presenting the results in a table, the scenarios are described analytically.

In the first scenario, passenger demand is low and stop interference is minimal. The cumulative dwell time is

$D_1 = 2,1$ minutes.

Therefore, the route time becomes

$T_1 = 28,0 + 2,1 = 30,1$ minutes.

The predicted regularity level is

$R_1 = 98,67 - 4,68 \cdot 2,1 = 88,84\%$

or approximately 88,8%.

In the second scenario, passenger demand is moderate and several stops show longer boarding processes. The cumulative dwell time rises to

$D_2 = 3,0$ minutes.

The total route time becomes

$T_2 = 28,0 + 3,0 = 31,0$ minutes.

The predicted regularity level is

$R_2 = 98,67 - 4,68 \cdot 3,0 = 84,63\%$

or approximately 84,6%.

In the third scenario, demand is high, and the route begins to accumulate noticeable stop delay. The cumulative dwell time reaches

$D_3 = 4,2$

minutes.

The route time is then

$$T_3 = 28,0 + 4,2 = 32,2$$

minutes.

The predicted regularity becomes

$$R_3 = 98,67 - 4,68 \cdot 4,2 = 79,01\%$$

or approximately 79,0%.

In the fourth scenario, the route experiences high passenger exchange together with strong crowding at key stops. The cumulative dwell time rises to

$D_4 = 5,1$ minutes.

Hence, the route time becomes

$T_4 = 28,0 + 5,1 = 33,1$ minutes.

The expected regularity level falls to

$$R_4 = 98,67 - 4,68 \cdot 5,1 = 74,80\%$$

or approximately 74,8%.

The difference between the first and fourth scenarios is operationally important. The cumulative dwell time increases by

$5,1 - 2,1 = 3,0$ minutes,

while the regularity level decreases by

$$88,8 - 74,8 = 14,0$$

percentage points.

This means that even without changing route length or fleet size, stop-level dwell effects alone can cause a substantial deterioration in route regularity.

Results and Discussion

The experiment confirms that dwell time should be treated as a primary operational determinant of urban bus regularity. The relationship is not merely descriptive. The model provides an explicit coefficient that can be used in planning and dispatch decisions. In the present case, the dwell-time sensitivity coefficient equals

$$k_d = -4,68$$

percentage points per minute.

This value is highly practical because it translates stop-level inefficiency into route-level regularity loss.

The model also shows why some routes become unstable even when their timetable appears reasonable on paper. If several high-demand stops generate additional dwell time simultaneously, the cumulative loss quickly propagates along the route. As a result, buses depart late from downstream stops, headways become uneven, and bunching risk increases.

Another important result is methodological. The stop-level equation and the route-level equation complement each other. The first explains where the delay comes from. The second explains what that delay does to service regularity. This two-level structure is more useful than a single aggregate percentage because it allows the analyst to move from diagnosis to intervention.

From a transport-management perspective, the model suggests several operational uses. If a route is known to have unstable regularity, the agency can identify whether the main cause is excessive boarding time, high alighting concentration, or crowding at a small number of critical stops. The same model can then be used to estimate the expected regularity gain from faster fare collection, all-door boarding, better stop design, or dispatch intervention at the critical points.

Conclusion

This paper developed an improved mathematical model for assessing the influence of bus stop dwell time on urban bus service regularity. The model integrates two analytical levels: a stop-level dwell-time function based on passenger activity and crowding, and a route-level regularity equation based on cumulative dwell time.

The computational experiment showed that an increase in cumulative dwell time from 2,1 minutes to 5,1 minutes reduced the expected regularity level from 88,8% to 74,8%. The resulting equation

$$R = 98,67 - 4,68D$$

demonstrated that each additional minute of cumulative dwell time decreases regularity by 4,68 percentage points.

The practical significance of the model lies in its applicability to stop diagnostics, route monitoring, dispatch planning, and timetable revision. It can be used to identify the most problematic stops, quantify their operational impact, and support interventions aimed at improving regularity.

In further research, the model may be extended by introducing time-of-day differentiation, stochastic passenger arrivals, stop-type heterogeneity, and real APC or AVL datasets. However, even in its current form, it provides a clear mathematical basis for linking stop dwell time to route-level bus service regularity.

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