Optimal boarding and alighting operations in urban mass transit

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Urban rail operations are characterized by short headways, under which even minor station delays can rapidly spread through the network [1]. One of the main sources of such delays is station dwell time, defined by the duration required for passenger boarding and alighting. Dwell times are particularly prolonged when passengers concentrate at a limited number of doors, since train departure is governed by the door with the highest boarding and alighting load [4]. Most existing approaches to reduce dwell-time delays focus on local crowd-management interventions or timetable-based measures [3]. However, door-level imbalances persist along a line: passengers who board at a specific door later alight at downstream stations, shaping subsequent dwell times and capacity conditions. While counterflows at doors are well established as a primary determinant of dwell time [2], passengers' door-choice behavior and the potential for actively redistributing passengers along platforms remain largely unexplored.

We contribute to the literature by proposing a network-wide optimization framework that minimizes total train dwell time by influencing passenger distributions across doors via incentives. The framework (i) assigns origin–destination demand to feasible passenger paths in a time–space network, where each path is defined by a sequence of boarding and transfer door choices and is subject to in-vehicle capacity constraints; (ii) embeds a discrete choice model to capture passengers' preferences over alternative paths characterized by boarding and transfer door choices and their responses to incentive schemes, and (iii) computes train dwell times using a door-specific dwell-time function, with overall dwell time governed by the most heavily loaded door.

1 Solution approach

We propose an integrated passenger flow management framework that jointly models door-level operations, passengers' behavioral responses, and network-wide effects over time. The resulting decision problem is formulated as a nonlinear and *nonconvex* **mixed-integer nonlinear program (MINLP)**, arising from bilinear terms in the door-level dwell-time function and in the choice-based passenger allocation, as well as discrete incentive levels activated via binary decision variables.

Passenger movements are modeled through a set of feasible paths connecting origin-destination pairs, where each path is defined by a sequence of boarding and transfer door choices across one or multiple train trips. Train schedules are assumed to be fixed, and passenger demand is assigned to paths subject to in-vehicle capacity constraints. We assume that passengers typically use the same door for boarding and alighting within a train trip, reflecting crowded operating conditions where repositioning inside the vehicle is unlikely [6].

Passenger preferences for paths are captured by embedding a discrete choice model. Path utilities are determined by door-related attributes characterizing the path, such as proximity to station entrances, transfer requirements, and economic incentives (e.g., door-specific discounts). The resulting utilities provide choice probabilities for each path and thus the expected boarding volumes per door.

Train dwell time is determined at the door level as a function of boarding and alighting volumes. For each station and trip, door-specific dwell times are aggregated such that the overall train dwell time is governed by the most heavily loaded door. This formulation captures how local imbalances at individual doors propagate to train-level delays and, through capacity constraints, affect passenger flows at subsequent stations.

The resulting optimization problem determines incentive levels that minimize total dwell time across the network by redistributing passenger flows across alternative paths. The optimal path assignment and incentive design must be determined jointly, as passenger flows are not directly controllable but emerge endogenously from the choice model. A sequential approach generally leads to state-inconsistent solutions, since deviations in realized flows affect downstream onboard loads and subsequent capacity constraints. We solve the nonconvex MINLP using off-the-shelf MINLP solvers and report best feasible solutions within specified time limits and solver tolerances.

2 Computational experiments

We evaluate the framework on a small test instance with two lines, five stations, and four doors per train. The model is implemented in GAMSPy and solved using SCIP with a computational time limit of 96 hours. The experiments were executed on a Mac Studio (macOS Tahoe 26.0, with 192 GB of RAM). We compare the approach against two benchmarks, namely a uniform and a skewed door distribution. The optimized solution achieves a system-wide dwell time of 376.22 s, compared to 376.75 s under a uniform distribution and 488.33 s under a skewed distribution, corresponding to reductions of approximately 0.14% and 29.8%, respectively. The small gap to the uniform benchmark is expected, as the limited instance size (in terms of number of doors and passenger volumes) restricts the potential for reducing counterflows at train doors. Consequently, a uniform distribution already performs close to the optimized solution. We expect the performance gap to increase with larger instance sizes.

3 Future work

The effectiveness of incentive-based passenger redistribution depends strongly on behavioral parameters, particularly passengers' price sensitivity. Future work will therefore focus on estimating discrete choice model parameters through stated-preference experiments that capture responses to door-specific incentives and transfer attributes. In addition, the results are sensitive to the specification of the door-level dwell-time function, especially the weights associated with boarding–alighting counterflows. These parameters will be calibrated using real-world operational data and agent-based simulation.

A further limitation of the current model is the assumption that passengers preselect a complete path, including door choices at transfer stations. This limitation will be addressed by adopting a recursive logit framework [5], allowing for dynamic door-choice decisions during the journey.

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