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Transportation Research Procedia 22 (2017) 65–74

Transportation Research Procedia

www.elsevier.com/locate/procedia

19th EURO Working Group on Transportation Meeting, EWGT2016, 5-7 September 2016, Istanbul, Turkey

A Transit Bottleneck Model for Optimal Control Strategies and its Use in Traffic Assignment in Paris

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Abstract

Control strategies are of crucial importance in operations of saturated transit lines. At a given bottleneck, delay propagates due to an excess of demand over supply. Operators therefore use optimal strategies (e.g. holding, fast-running, train-canceling etc.) in order to recover the level of service. While toolbox for train operation control system has thrived in past years, few traffic assignment models for large-scale transit networks on the planning side have touched on the impact of control dynamics: static macroscopic models perform quite well in simulating platform/vehicle saturation, but less so with bottleneck delay; dynamic models deal with dynamic passenger behavior under congestion, yet single vehicle runs are not explicitly considered either.
The objective of this paper is to (1) capture the dynamic control features in a bottlenecked rail system; (2) provide a computation-friendly simulation approach to optimize the control; and finally (3) fit the bottleneck model in a static capacitated assignment model to improve its performance. The paper first provides mathematical formulae to describe bottleneck phenomena in a high-demand high-frequency transit line. Formulae are then cast into a control problem of dynamic system, to which we apply dynamic programming to reduce the dimension of decision variables. A numerical application to the Line RER A in Paris is followed, in which control strategies are optimized at key stations in a rolling horizon; on-platform passenger activities are simulated accordingly. Results are compared with both static model and real-life data, showing the effectiveness of the control-based assignment.

Peer-review under responsibility of the Scientific Committee of EWGT2016.

Keywords: Transit Bottleneck; Traffic Assignment; Control Strategies; Delay Recovery; Dynamic Programming

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2214-241X
Peer-review under responsibility of the Scientific Committee of EWGT2016.
10.1016/j.trpro.2017.03.010

1. Introduction

Bottleneck delay stems mainly from the excess of demand over supply, as a direct consequence of ordinary peak-hour saturation. At the source ("bottlenecked") station, willing-to-board passengers delay doors' closing and trains' departure. Delay then accumulates through knock-on effect and propagates upwards and downwards along the transit line. Service frequency decreases; platform congestion grows: the service is caught in a vicious cycle. One typical example is the Line RER A in Paris, one of Europe's busiest transit lines with over 1 200 000 passengers per day. During the morning peak, the service is severely delayed as a result of the huge demand. Report (STIF, 2012) shows that westbound service frequency is reduced by 19% on average, from 30 to 24.4 trains per hour.

Pender et al. (2012) find it an established practice to use rescheduling strategies (holding, fast-running and train-canceling) in order for operators to deal with bottleneck delay, with which the level of service can be effectively recovered with a relatively low control cost. However, past research on transit traffic assignment models has not totally explored it. Some assumed that frequency reduction effect does not propagate; many others adapted the reduced frequency uniformly to all stations. Both simplifications appear to be off from real-life practice, failing to simulate not only the spatial and temporal accumulation of delays, but also the efforts made by operators to apply dynamic controls for schedule recovery.

The paper aims at modeling the bottleneck delay along with the control strategies for its recovery, and finally adding dynamic operation features to the static assignment model. The rest of the paper is divided into four parts: Section 2 reviews different approaches of modeling bottleneck dynamics in the literature, linking the perspectives from both planning side and operation side. Section 3 develops the mathematical model, which describes operation conditions (rolling stock, passenger activity), system constraints (rail capacity, signaling system) and operators' skillset in bottleneck recovery. The mathematical model is transformed into a dynamic programming problem, leading to an approximate solution which significantly reduces the computation time. In section 4, an application instance based on RER A is carried out, targeting a high-frequency rail transit system of both headway-based and schedule-based regulations. The results demonstrate how different strategies may influence the level of service. Section 4 also justifies the compatibility of this bottleneck model with the traditional traffic assignment models. Section 5 draws the conclusion of the study and indicates some directions for further research.

2. Bibliographical Review

On the planning side, traffic prediction follows the sequential four-step process, traffic assignment being the last step. While early static transit assignments usually assumed free-flow boarding and running, many recent studies have been focused on congestion condition. Lam et al. (2002) propose a formulation for the capacity restraint assignment, in which line frequency is related to the passenger flows due to the fixed fleet size. Leurent and Liu (2009) and Schmöcker et al. (2011) study the seat capacity as another factor of congestion. Leurent et al. (2014) deal with a larger range of capacity phenomena and demonstrate that frequency also depends on track occupancy, since vehicle clearance time and safety margins have to be ensured. A static traffic assignment model is put forward to simulate the bottleneck: downstream frequencies are reduced by the same value; upstream links share the delay by increasing the running time. However, this model does not consider bottleneck phenomena as dynamic.

Dynamic assignment models, on the other hand, have been largely focused on passenger behavior. Nuzzolo et al. (2012) present a schedule-based model to investigate vehicle congestion, in which user behavior is affected by on-vehicle discomfort and operational delay. Schmöcker et al. (2008) propose a frequency-based dynamic approach, with attention being paid to platform congestion and passenger queuing caused by bottleneck. The "failing-to-board" probability is introduced in their study, thanks to which the simulated wait time gets much closer to the real case. However, it's still underestimated due to the strongly simplifying assumptions about service regularity

On the operation side, near-capacity operation has been long tied to control strategies. Eberlein et al. (2001) analyze real-time control strategies with a general model. Their deterministic model tests the strategies of holding, stop-skipping and deadheading. Shen and Wilson (2001) add the delay to the system. The results show that holding strategies combined with short-turning can reduce the objective by about 10-60%. Sánchez-Martínez et al. (2015) formulate a holding optimizing model that reflects dynamic running times and demand. The model proves that control based on dynamic inputs outperforms its static equivalent in overcrowded cases and optimization-based