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A dynamic stochastic model for evaluating congestion and crowding effects in transit systems

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ABSTRACT

One of the most common motivations for public transport investments is to reduce congestion and increase capacity. Public transport congestion leads to crowding discomfort, denied boardings and lower service reliability. However, transit assignment models and appraisal methodologies usually do not account for the dynamics of public transport congestion and crowding and thus potentially underestimate the related benefits.

This study develops a method to capture the benefits of increased capacity by using a dynamic and stochastic transit assignment model. Using an agent-based public transport simulation model, we dynamically model the evolution of network reliability and on-board crowding. The model is embedded in a comprehensive framework for project appraisal.

A case study of a metro extension that partially replaces an overloaded bus network in Stockholm demonstrates that congestion effects may account for a substantial share of the expected benefits. A cost-benefit analysis based on a conventional static model will miss more than a third of the benefits. This suggests that failure to represent dynamic congestion effects may substantially underestimate the benefits of projects, especially if they are primarily intended to increase capacity rather than to reduce travel times.

1. Introduction

Transit assignment models (TAM) are used for predicting the distribution of passengers over a transit network. These models therefore play a critical role in evaluating the benefits of alternative network extensions as part of project appraisal. In many cities, insufficient capacity is perceived as the most serious problem in the public transport system, resulting in crowding, unreliability and long waiting times. However, appraisal methodologies for projects meant to increase capacity are relatively less well developed than methodologies for projects aiming to reduce travel times. Neglecting congestion-relief benefits results in an underestimation of the total benefit of an investment.

We present a method to capture the benefits of improved capacity more adequately by using a dynamic and stochastic TAM which accounts for dynamic congestion and crowding effects. The capabilities of the model are illustrated with a case study of a planned metro extension in Stockholm, Sweden, which exemplifies the magnitude of congestion-related effects when compared with nominal travel time savings as well as with the results of a conventional transit assignment model.

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In the following, *congestion* in public transport refers to phenomena that are caused by high density of passengers and/or vehicles, which results in decreased service performance. A more saturated network element leads to an increase in the generalized travel cost. One of the effects of congestion is *crowding*, which refers to lower on-board comfort as the on-board load increases.

The main contributions of the study are:

- To the best of our knowledge, this is the first study that considers the dynamics of public transport congestion in appraisal of large public transport investments.
- The development of a dynamic and stochastic TAM which represents the evolving interrelation between service reliability and passenger crowding and delay.
- The model is implemented in an agent-based public transport simulation model.
- The model is integrated in a project appraisal framework and the projected welfare benefits are compared with the results obtained from a state-of-the-practice static assignment model.
- A simulation study of the congestion and crowding impacts of a large-scale real-world case study where an extensive but overloaded bus network in Stockholm is partially replaced by a metro line.
- A demonstration of how the proposed model captures congestion and crowding relief benefits which are neglected by conventional static models.
- Our simulation results suggest that the benefits that stem from including dynamic congestion and crowding effects in the analysis amount to at least one third of the total passenger benefits.

Three distinct public transport congestion effects are considered: (1) *On-board discomfort* – crowding in the vehicles increases the value of time of passengers and hence their generalized travel cost; (2) *Denied boarding* – if the vehicle has no residual capacity, some passengers will be denied boarding and have to wait for the next vehicle. (3) *Irregular vehicle arrivals* – boarding and alighting passenger flows as well as on-board passenger load are among the main determinants of dwell times at stops. The relation between passenger flows, dwell times and headways between successive vehicles results in a positive feedback loop that amplifies fluctuations in headways and gives rise to the bus bunching phenomenon. Insufficient capacity can therefore result in delays and reduced service reliability.

The developed model addresses the main challenges that were identified by Liu et al. (2010) in their review of TAM, dealing with supply uncertainties and adaptive user decisions. They identified the dynamic loading process and the agent-based simulation as two potential approaches, which are both utilized in this study.

The remainder of this paper comprises six sections. Section 2 presents a literature review on modelling congestion in TAM. Section 3 presents the dynamic model we propose for modelling congestion effects. Section 4 presents the application and its specifications. Section 5 presents the results from the case study, followed by a discussion of their implications on the cost-benefit analysis as compared with a schedule-based assignment model in Section 6. Section 7 presents the main conclusions and outlines directions for further research.

2. Literature review

There is a growing literature on modelling congestion in TAM with a remarkable increase in interest in the last decade, see a review by Fu et al. (2012). TAMs are conventionally classified into frequency-based and schedule-based models, differing in their network supply representation and its implications for the passenger loading procedure. Previous studies have developed a number of approaches to address congestion in transit networks. Most of the developments have focused either on accounting for on-board discomfort or on considering capacity effects on passengers' queuing. Flow-dependent in-vehicle times were introduced already in the seminal work by Spiess and Florian (1989). They suggested penalizing congested links by assigning travel times that were increasing functions of the *flow-capacity ratio multiplier*, inspired by the BPR function used in traffic assignment. This approach was then adopted by Lam et al. (1999) and Hamdouch et al. (2011). de Palma et al. (2015) formulated the user equilibrium and optimal equilibrium for a crowding definition inspired by the BPR function as well as for two alternative step functions. Alternatively, the congestion effect could be considered through assigning weights to waiting times by computing the *effective frequency* (de Cea and Fernández, 1993; Cominetti and Correa, 2011), hence shifting the travel impedance caused by congestion from links to nodes. This approach is based on queuing theory where waiting times becomes infinite at flow saturation. Szeto and Jiang (2014) formulated frequency-based TAM as a link-based variational inequality where the travel cost function includes a term for the additional waiting time due to in-vehicle crowding when headways are assumed to be perfectly irregular.

Both the flow-capacity ratio multiplier and the effective frequency methods discourage passengers from choosing saturated links. However, they do not guarantee that capacity will not be exceeded. Nuzzolo et al. (2001) and Cepeda et al. (2006) introduced an infinite penalty for exceeding total capacity in schedule- and frequency-based assignment models, respectively. Similarly to static traffic assignment models, static TAMs do not guarantee that capacity is not exceeded, as all passenger demand is loaded onto the network even if it cannot be absorbed by the capacity available. Cepeda et al. (2006) applied a capacitated equilibrium static transit assignment model for the Stockholm transit network. The iterative process reduced the number of oversaturated links but retained flow/capacity ratios exceeding one without reaching a feasible flow distribution. This is especially important for highly-saturated networks where capacity constraints are binding for important network elements.