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A traffic assignment model for passenger transit on a capacitated network: Bi-layer framework, line sub-models and large-scale application

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ABSTRACT

In the urban setting, the roadway and railway modes of mass transit are basically purported to carry large flows of passengers. Thus the issue of flowing capacity is crucial in the design and planning of a transit network. As a transit system involves two types of traffic units, respectively passengers and vehicles, there is a broad range of capacity phenomena: (i) as a vehicle has given seat capacity, additional riders have to stand which is less comfortable and more exposed to in-vehicle crowding, (ii) the total capacity in a vehicle, including sitting and standing places, influences the wait time on platform if it is exceeded by the number of candidate riders, (iii) the exchange capacity at vehicle doors influences the vehicle dwell time at a station, (iv) from the station dwell times stems the run time of vehicles – hence of passengers – and in turn the service frequency, (v) vehicle traffic is constrained by dwell time and operating margins, which may reduce the frequency delivered, etc. The paper provides a static, macroscopic model of traffic assignment to a transit network, in which these capacity phenomena are captured. A key feature is the line sub-model that deals with a line of operations, comprised of one or several service routes, by using the topological order of stations. From a matrix of flows by pair of access-egress stations, the sub-model derives the matrix of average passenger costs by access-egress pair, as well as local passenger wait time and the apparent frequency of each leg. At the network level, passenger route choice is modeled by optimal hyperpaths that are route-based (as in De Cea and Fernandez, 1989). It is shown that there exists a state of traffic equilibrium. A Method of Successive Averages is put forward to compute equilibrium. A large scale application to the whole transit network of greater Paris is presented, with focus on capacity issues.

1. Introduction

Background: Every mode of public transportation for passengers involves two types of traffic units: the passengers that act as individual trip-makers versus the vehicles that serve the passengers according to operational protocols. These include the scheduling of service runs, the access and egress of passengers to and from vehicles at predefined transit stops, the holding of operational margins, etc. The duality of traffic units gives rise to a rich set of traffic phenomena, including a range of capacity

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issues. These are described at length in the Transit Capacity and Quality of Service Manual – hereafter TCQSM for short (TRB, 2003), starting from the sitting and standing capacities inside a vehicle. Then, between a vehicle and a station platform, there is also the issue of exchange capacity due to the number and width of the vehicle doors as passenger channels. Next, platform layout and station layout determine the capacity of pedestrian elements such as areas for storage or walking corridors. Furthermore, vehicle traffic is constrained by interaction with other flows on roadways or simply by safety margins between two successive trains on a railway. The TCQSM emphasizes the influence of capacity on the quality of service delivered to the passenger. It is purported to be used in the analysis and design of transit sub-systems, from stop to line and intermodal stations. The design settings should be adapted to passenger flows that are not known ex ante: so it is very important to simulate the flows with sufficient accuracy.

This duty is the very aim of a model of traffic assignment to a transit network: such a model is used to simulate the trip flow by network element on the basis of both the network structure and the trip demand in an adequate study area. The main component in an assignment model is the simulation of passenger route choice at the disaggregate level of the individual trip, since it enables one to capture important network effects between transport services: the diverse paths used by the trip-makers put the services in both complementariness (sequential composition) and competition (parallel composition), thereby in "weak" interaction mediated by the path flows. Another important component in a network assignment model is the simulation of traffic phenomena such as congestion laws. Overall, the assignment model captures the interplay between these physical phenomena and the passenger route choice that is a behavioral, microeconomic process. The integrated representation of relevant phenomena and behaviors is all the more important for a transit network as it carries larger flows, of which the diversion from one service to another one could change the quality of service by large.

It turns out that, while the toolbox for roadway network planning and management has thrived in the past decades, the toolbox for transit network planning and management has been less intensively developed. In the transportation planning software that are commercially available worldwide, most notably the Cube, Emme/3, Transcad and Visum softwares, there are transit assignment models either static or dynamic to deal with route choice fairly well, but less so with capacity phenomena. The main features that have been modeled so far are, first, in-vehicle crowding with simplistic if any consideration of seat capacity, second, the effect of boarding and alighting flows on vehicle dwelling times at stations, third, the addition of congested dwell times along service routes to yield route time under congestion (TransITS, 2014). Although this subset of phenomena is wider than that in roadway assignment, it is still much incomplete with respect to the real-world performance of transit networks – thus calling for research on their modeling.

Related work: An extensive review of scientific literature is supplied in the next Section. Put simply, a number of models have been developed to address either in-vehicle crowding, or total vehicle capacity and the associated wait time before boarding, or seat capacity, or some frequency effect. However, there have been few attempts to integrate a wide range of capacity phenomena in a coherent model of traffic assignment to a transit network. Bellei et al. (2000) featured out such an integrated model in a static, link-based, frequency-based, user equilibrium framework, including (i) in-vehicle congestion, (ii) dwell-time congestion due to boarding and alighting flows, (iii) vehicle traffic congestion, (iv) an eventual frequency reduction in case of increased vehicle cycle time. Their contribution has pioneered the dynamic model of Meschini et al. (2007), in which the station wait time stems from a traffic bottleneck. No large size application has yet been reported for a dynamic traffic assignment model capturing several capacity phenomena, whereas static models of one or two capacity phenomena have been applied to the networks of Stockholm (Cepeda et al., 2006) and Paris (Leurent and Liu, 2009).

Objective: The objective of this paper is to bring about a model of traffic assignment to a transit network, dubbed CapTA for Capacitated Transit Assignment, which integrates a large set of capacity phenomena in a coherent way. The following traffic phenomena are modeled explicitly:

(i) In-vehicle seat capacity with priority rules for seat access and travel cost sensitive to comfort state.
(ii) Total vehicle capacity is enforced, with effect on station wait time on the passenger side; passenger mingling is assumed at waiting, as in Kurauchi et al. (2003).
(iii) Vehicle dwell-time at a station depends on the boarding and alighting flows and the exchange capacity.
(iv) By leg between any pair of stations along a transit route, as the vehicle run time includes the station dwell times, it is sensitive to congestion: this induces the leg physical time to the passenger.
(v) By line station, the track occupancy by the dwelling and clearance of vehicles as well as the operational margins can reduce the nominal frequency down to an effective frequency. This is propagated downstream along the line.
(vi) The alteration of service frequency yields an average vehicle delay which is propagated upstream along the line.

Most of the partial models are taken from previous work. The waiting model and the frequency model are well-suited to railway services in the urban setting. The salient features of the CapTA model are the coherent integration of the phenomena and their interplay with passengers' route choices – through the quality of service that depends on the local traffic conditions. The overall integration enables one to simulate complex interactions along a transit line between service frequency, local residual on-board capacity, dwell times and run times. On the passenger side, travel strategies are based on generalized times and the dynamic availability of transit services, leading to frequency-based user equilibrium as in Spiess and Florian (1989) yet with leg-based route options as in De Cea and Fernandez (1989). In this respect, an innovative model feature is the alteration of frequency in the local route choice proportion of a service when it is so congested that its selection by a trip-maker amounts to join a waiting queue rather than to wait and board in the first incoming vehicle.