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Integrated traffic-transit stochastic equilibrium model with park-and-ride facilities ☆

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ABSTRACT

We propose an Integrated Stochastic Equilibrium model that considers both private automobile traffic and transit networks to incorporate the interactions between these two modes in terms of travel time and generalized costs. In addition, in the general version of the model, travelers are allowed to switch from personal vehicles to mass transit at specific locations in a park-and-ride scheme. The assignment for traffic equilibrium is based on the Markovian Traffic Equilibrium model of Baillon and Cominetti (2008), whereas the equilibrium of the transit network is represented by the Stochastic Transit Equilibrium model of Cortés et al. (2013). Stochastic travel decisions are made at the node level, thereby avoiding the enumeration of routes or strategies and incorporating various perception and uncertainty issues. We propose a Method-of-Successive-Averages algorithm to calculate an Integrated Stochastic Equilibrium and conduct numerical experiments to highlight the effect of stochasticity on equilibrium flows and travel times. Our experiments show that higher stochasticity implies greater dispersion of equilibrium flows and longer expected travel times. Results on a real network with mode combination and park and ride facilities provide insights regarding the use of park and ride in terms of number and location, potential modal share of the combined mode option under different circumstances, and travel time impact due to the implementation of such park and ride facilities in a real setting.

1. Introduction

Over the past two decades, many cities worldwide have grown considerably in terms of both population and land use, thereby generating new demands on transportation offerings for their inhabitants. This has motivated the interest of researchers and practitioners in modeling urban networks at different scales for various purposes. In this context, the use of urban planning models to assess investment policies for improving the welfare of people has become an important issue. At a strategic level of analysis, the so-called assignment and user equilibrium models are designed to reproduce the observed

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behavior and choices of individuals with respect to transit and traffic networks. On the one hand, transit equilibrium models seek to reproduce the boarding and alighting stops and route choices in terms of the utilized transit lines; on the other hand, traffic equilibrium models seek to reproduce the route choices in an urban road network. In the specialized literature, most articles on assignment and equilibrium models that explore pure modes, focused their analysis on the case of traffic networks, which generally rely on Wardrop's principle. Wardrop's principle states that rational users select routes that minimize their expected travel time. In turn, many existing transit equilibrium models have adopted this principle. However, there is an irremediable difference between traffic and transit modes: while choosing the route that minimizes the on-board expected travel time is sufficient in the case of traffic, in the transit dimension, the route choice is defined by the particular bus that a passenger boards within a set of different common lines that serve a bus stop that can be used to reach the destination. Subsequently, in addition to considering the on-board travel time when using the vehicle, in the transit dimension, the waiting time also plays an important role and is linked to other variables inherent to any transit system such as frequency and bus capacity.

The majority of the recent literature has focused on modeling preferences by assuming that passengers choose a route *strategy* for their trips. Inspired in Chriqui and Robillard (1975), Spiess and Florian (1989) defined a strategy as a set of rules that, when applied, allow a passenger to reach his/her destination. A well-formulated strategy includes the choice of the attractive lines set at a stop; furthermore, this concept assumes that users have complete knowledge of the network structure and the conditions for recognizing and using effective strategies (Bouzaïene-Ayari et al., 2001), which may appear unrealistic in situations with high traffic congestion and interaction of modes. Over the past 20 years, there has been a trend in transportation policies toward improving public transportation attractiveness by decreasing the volume of cars moving on streets and encouraging modal interchange. Hence, *park-and-ride* (P&R) facilities have emerged in specific locations of urban zones to facilitate the first leg of the trip being conducted using a personal car, followed by the second leg completing the trip through a massive and efficient mode of public transit, namely trains, buses, or subways. These trips are performed by a non-unique transportation mode known in the literature as combined modes. The incentive for users to choose these combined modes is associated with congestion on the streets, frequency and fares of transit services, and the location of parking facilities. To better reflect what occurs in large urban centers, we address the previous issues by means of combining two features: mode integration and stochasticity in travel decisions.

The goal of the present paper is to develop an Integrated Stochastic Equilibrium model that considers both traffic and transit networks to incorporate the interactions between the two pure modes in terms of travel time and generalized costs. The integrated formulation combines the Markovian Traffic Equilibrium (MTE) model developed by Baillon and Cominetti (2008) for the traffic network and the Stochastic Transit Equilibrium (STE) model of Cortés et al. (2013) for the transit network. Both models share similarities in their formulation because travel decisions are made in both cases at the node level, thereby avoiding the enumeration of routes or strategies. Moreover, both approaches include the effect of congestion at the vehicular and passenger levels in addition to stochasticity as a central feature, thereby allowing the inclusion of the various perceptions and uncertainty issues that people have regarding the features and conditions of the urban network. We emphasize that in this work *stochasticity* refers only to users perception of the level of service and not to other sources of uncertainty, such as stochasticity of travel demand and network supply. In addition, our model adds the combined mode option into the analysis, allowing users to transfer from car to transit at P&R facilities. More recently, Liu and Meng (2014) proposed a stochastic model on multimodal network, focused on bus-based P&R services, as well as elastic demand and congestion pricing charges. Although a probit-based stochastic transit equilibrium is assumed, which is relatively a new topic in literature, and the interaction between cars and buses in terms of travel time are largely analyzed, the framework proposed follows the common lines method adopted in De Cea and Fernández (1993), solving a mixed integer programming problem in order to determining the attractive line set between consecutive nodes in the transit network, and hence, computing a strategy for each transit user. Using the STE model in the integrated formulation that we propose, avoids the neither enumeration nor computation of routes or strategies.

To make this proposal applicable to real modeling conditions, we also propose an algorithm that performs the resulting stochastic equilibrium over a generic traffic and transit network, which is tested with real data of a city using, on the transit side, a logistic function for the boarding probability at bus stops and, on the traffic side, a Gumbel distribution for the error term in expected travel times. In this paper, in addition to developing the integration details, we apply the algorithm to a realistic case study corresponding to a medium-sized network of the city of Iquique, Chile.

The primary objective of the Integrated Stochastic Equilibrium model is to become an urban planning tool for transportation decision makers. The model should be calibrated in a case-by-case modality to be able to reproduce the current passenger and vehicle flows observed on the streets. Such a tool can thereby become a powerful prediction model of user behavior when relevant changes to public transportation or road infrastructure supply are implemented.

The remainder of this paper is organized as follows. First, we present a literature review of related topics. In the next section, we describe the transportation network and introduce the notations used throughout the paper. Next, in Section 3, we provide the definitions of Integrated Stochastic Equilibrium with Pure and Combined Modes. Then, in Section 4, the solution algorithms are presented. In Section 5, we present the results of various experiments to demonstrate the potential and consistency of the stochastic formulation under different scenarios. In Section 6 we report the implementation of the model in the real network of Iquique. The paper closes with a summary, conclusions and ideas for further work.