TITLE OF THE DOCTORAL THESIS

Dynamic multi-user and multi-scale traffic equilibrium model for urban networks

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1. CENTRAL RESEARCH QUESTION AND HYPOTESHES

One important issue with regard to the planning process of most urban transport systems is the capability of forecasting the traffic flow conditions that are expected to happen on the corresponding urban network in a future time horizon. In the case of private cars, when the objective is to study strategic transport plans, the most utilized tool by planners is to carry out the traffic flow equilibrium, based on the equivalent optimization problem that allow finding the static equilibrium of the private traffic assignment problem on large-scale urban networks (macroscopic approach). In such a problem, the decision variables are the aggregated flows of vehicles on each link within the modeled network. Moreover, each link is characterized by a traffic-flow delay performance function, which normally depends on the flow on such a specific link. Total travel time along each route (connecting an origin-destination pair) is computed as the summation of the travel time of each link in the route.

One limitation of such a static approach is that this modeling scheme does not recognize that urban networks are utilized by different type of users, with different driving habits and other features that clearly affect the motorists' behavior when sharing the infrastructure with other motorists (social, economical, cognitive, and so on). Although these restrictions are somehow overcome by micro-simulation approaches, in this thesis the objective is to include these features in the context of a city-scale equilibrium formulation.

We think that such an important limitation can be overcome by recognizing the existence and interaction of different motorists and by disaggregating the total flow on each link by user type, at a mesoscopic level. This differentiation will allow us treat more realistically the interrelations that occur on the network while travelers are moving from origins to destinations.

The major goal of this research is to develop a multi-user dynamic formulation of the network equilibrium problem for a generic urban network, considering processes at multiple scales. In this formulation, at the lower level we will recognize different behavioral patterns of individuals sharing the network infrastructure, which will result in link performance functions also differentiated by user type. At a more aggregate or upper level we will define the equilibrium conditions in the network at any point in time. The model will have the capability of considering negative externalities (caused by congestion) on links and nodes, also differentiated by user type, and characterized by the interaction between different users with different behavior.

Among the major contributions we identify by using this approach with respect to macroscopic equilibrium models, we highlight the followings:

<u>Travel times on links:</u> In the classical formulation, all vehicles that cross a link experience the same delay (average link delay that should include the link delay as well as the extra delay at the downstream node). If different user classes are considered, travel times could be different for different users, and that effect could be added to the modeling framework. Besides, the delay of each user before the presence of congestion will depend on the relative flow of the different types of users sharing the link, recognizing different degrees of externality between different users, and on the characteristics of the infrastructure.

<u>Differentiate behavior at a node level:</u> The interactions at intersections are not explicitly considered in macroscopic models. When different users are now differentiated, it is necessary to model the detail of the operation at each intersection to capture different behaviors and interactions.

<u>Dynamic approach:</u> Given the features of our modeling approach differentiated by user type, we strongly believe that the dynamic dimension has to be added into the optimization at the proposed mesoscopic level. From that, we will be able to model the alterations in behavior as a result of the cumulative time the users have been traveling within the network, and that will be sensitive to the type of the user for various congestion levels and interactions. Including the dynamic dimension in the assignment for different users is a challenge and will be a central

issue of the development of this thesis work. There have been some efforts in the specialized literature to solve the dynamic traffic assignment problem, by adding the temporal component to the analysis (see next section for a brief review of the literature in this area); however, the dynamic approaches have not focused on including the motorists´ behavior in the way we think it is necessary to take into account the real interactions and mesoscopic relations that occur among drivers of different type.

<u>Consistency with macroscopic level:</u> The approach has to be consistent with the aggregation at a macroscopic level, in terms of consistency in average level of service and traffic conditions considering the interactions through time and space.

By following the previous arguments and ideas, we identify at least four main hypotheses for this thesis work:

1. Differentiating the individual user behavior strongly affects the equilibrium schemes. This phenomenon cannot be modeled by using the traditional traffic equilibrium aggregate models.
2. The dynamic component is essential in several contexts: interactions between agents, decision process, and intensity of trips. Dynamic models have not been oriented to consider these issues so far.
3. Different traffic configurations involving different types of users generate completely different equilibrium states at an aggregate level.
4. The externalities that came from user interactions depend on the level of homogeneity of users that share the right of way.

2. BACKGROUND AND CONTEXT (LITERATURE REVIEW)

The trip assignment models determine the route to be followed by each traveler once the mode and destination have been decided (see Ortúzar and Willumsen, 2001). The situation has been frequently described as a game where traffic is seen as some sort of steady state in which travelers have no incentive to deviate from their current decisions.

Here, we can recognize two approaches to deal with this problem: macroscopic and microscopic.

In the macroscopic models, since traffic involves many small players, a common approach is to ignore individual travelers and use continuous variables to represent aggregate average flows.

Congestion is then modeled by flow-dependent travel times and a flow pattern is called equilibrium if all used routes are optimal for these times. These aggregate models, also known as non-atomic or population games were introduced by Wardrop (1952) in a deterministic setting of identical players with perfect information. The variability in travel times and user perceptions led Dial (1971) to look at route selection in terms of random utility theory, and then a corresponding concept of stochastic user equilibrium (SUE) was investigated by Daganzo and Sheffi (1977). Wardrop equilibrium were characterized by Beckmann et al. (1956) as solutions of an equivalent convex minimization problem (see also Daganzo (1982) and Fukushima (1984) for a formulation using convex duality), and a similar characterization for SUE was obtained by Fisk (1980). For an historic account of traffic equilibrium we refer to the book Ben-Akiva and Lerman (1985) and the survey by Florian and Hearn (1999). A recursive property of the Logit model allowed Akamatsu (1997) to restate SUE in the space of arc flows, and inspired the general Markovian traffic equilibrium (MTE) in Baillon and Cominetti (2006). Unlike the previous equilibrium models which are route-based, the Markovian equilibrium models a chain of decisions where at each node the user decides the next link to get in, pursuing the minimization of the expected travel time to reach a predefined destination, regardless of the assignment decisions made before. Recently, Briceño et al. (2008) and Bravo et al. (2009), integrated the Markovian Traffic Equilibrium model of Baillon and Cominetti (2008) with the land-use equilibrium model called Random Bidding and Supply Model (RB&SM) by Martínez and Henríquez (2007), considering location externalities in the equilibrium decisions. The research group is now working on the implementation of an integration of transit and traffic, based on the Congested Transit Equilibrium model of Cominetti and Correa (2001), by means of a method to obtain modal choice and traffic and passenger assignments through Wardrop-equilibrium calculation in an extended fictitious network (Cortés et al., 2009a).

In regard to the microscopic approaches it is likely to recognize the presence of small players, and investigate the way they interact in traffic. The traffic components can be represented as entities interacting among themselves. The main entities in a traffic network are vehicles, road segments, junctions and traffic signals, which can be modeled as agents. These agents have the ability to perceive changes in their environment and, as a result, modify their behavior for a given objective. For example, the reaction of a driver to a given stimulus ahead can be to speed up to reduce his/her travel time. This is an old idea that had lead to the car-following models since the 1950s (TRB, 1997). Nowadays, however, this idea has been translated into computer code to produce powerful microscopic traffic simulation models ("traffic microsimulators" hereafter).

An analysis of many of these traffic microsimulators can be found in reports of the European SMARTEST (Simulation Modelling Applied to Road Transport European Scheme Tests) project, which analyzed the characteristics of 32 traffic microsimulators (Fox, 2000). Notice that in the case of microsimulation, the objective is to simulate the interactions at a micro level during the period of simulation. Therefore, the dynamic dimension is included in the analysis; however there is no proof that the equilibrium is reached, even though the rules for drivers to choose their routes is based on equilibrium concepts.

We guess that the modeling approach will require microsimulation of different agents to emulate different behavior and driving habits across drivers. One major issue in the implementation of different operational schemes for dynamic transport systems and the validation of the different models and algorithms is through a microsimulation of a real transport network and the agents interacting. Currently, we have a traffic microsimulation platform constructed to model transit systems Cortés et. al. (2009b) as well as specific fleets under the instructions of a central dispatcher (Cortés et. al., 2005). In this thesis we plan to make use of the simulation platform adapted to this particular case. The current tool was built as an Application Programming Interface (API), which allows incorporating specific transit models in the existing commercial traffic microsimulator PARAMICS (PARAllel MICroscopic Simulation). The platform makes advances in three simulation issues with respect to the existing software: the controlled vehicles can have new characteristics; passengers are incorporated and traced as individual objects; and specific models to represent the interaction between passengers and vehicles at stops are included. Moreover, a simplified abstract network (ABSNET) is constructed in order to run graph algorithms required for the optimization (shortest paths, TSP, etc.) according to the level of service that changes during the simulation. ABSNET has a correspondence with the network coded in the microsimulator, but contains only the nodes of interest for vehicle routing purposes.

In the recent years, another source of research has been developed: the dynamic traffic assignment (DTA) framework. DTA refers to a broad spectrum of problems, each corresponding to different sets of decision variables and underlying behavioral and system assumptions, and possessing varying data requirements and capabilities in terms of representing the traffic system or control actions. One common feature of these models is that they depart from the standard static assignment assumptions to deal with time-varying flows. Another feature shared by these models is that none presently provides a universal solution for general networks. Perhaps the one aspect that fosters unanimity among researchers is that the general DTA problem is inherently characterized by ill-behaved system properties that are imposed by the need to adequately represent traffic realism and human behavior. This is further exacerbated by the time-dependency and randomness in system inputs. A fundamental consequence of this reality is that a theoretical guarantee of properties such as existence, uniqueness, and stability can be tenable only through compromises in depicting traffic theoretic phenomena and potentially restrictive assumptions on driver behavior. Viewed from the complementary perspective, an ability to adequately capture traffic dynamics and driver behavioral tendencies precludes the guarantee of the standard mathematical properties. This inherent complexity of DTA has spawned a clear dichotomy of approaches that range from the analytical to the simulation-based. A fundamental practical consequence of the theoretical intractability is the focus of DTA researchers on developing deployable solution procedures that seek close-to-optimal solutions with a clear understanding that claims of uniqueness and/or global optimality are neither essential nor particularly meaningful in the real-world. This has manifested as the development of mostly heuristic implementation procedures that seek effectiveness, robustness, and deployment efficiency. Another outcome is the notion of commensurability of features among different approaches so that trade-offs among desirable features allow different degrees of responsiveness to different DTA problems given the broad scope of objectives and functional needs addressed under the general umbrella of DTA.

In the review of Peeta and Ziliaskopoulos (2001) are listened practically all the trends that are developed in the study of dynamic traffic assignment. Since the pioneering work of Merchant and Nemhauser (1978 a,b), numerous formulations and solutions approaches have been ranging from mathematical programming, to variational inequality, optimal control, and simulation-based models. There is currently heightened interest in DTA, particularly in the development of approaches that can be deployed for large-scale real-time and planning applications. In addition, researchers have become increasingly aware that the theory of DTA is still relatively undeveloped, which necessitates new approaches that account for challenges from the application domains as well for the fundamental questions related to tractability and realism. A reassuring practical aspect of the general DTA problem is that its mathematical intractability is not an all-encompassing barrier to the real-world utility of the associated solution approaches. Substantial research over the past decade suggests that effective and efficient solutions can be obtained for several realistic scenarios.

3. METHODOLOGY

As specific objectives, we plan to write the formulation for the dynamic equilibrium problem which leads to an optimization framework involving recursive and stochastic processes. The research is aimed at characterizing the solutions, finding mathematical conditions for existence and uniqueness, developing a consistent solution algorithm and testing the model on a simplified version of the Santiago city network, properly coded by following the model requirements.

1. To achieve these goals, in this thesis we have identified the following general work steps:
2. Formulation of a analytic mesoscopic model
3. Characterization of optimal solutions, existence and uniqueness conditions and analysis of stability of the model
4. Calibration and validation of the modeling framework
5. Experimental tests (future scenarios, cost-benefit analysis of urban plans and projects)

4. FIRST RESULTS

In this section we describe the current status of the thesis work. So far, we have accomplished the first task, which is to search on the specialized literature the type of formulations, methodological approaches and algorithms that could be useful to the development of the mesoscopic model proposed here. A summarized version of the literature review was summarized before in Section 2.

A second stage currently ongoing is related to the formulation of the problem itself; in this sense, we have advanced in understanding the problem to be modeled, and also in finding the conditions to ensure a doable formulation of a reasonably defined problem. In this line, we have identified two important issues related to the model:

- We claim that the traffic congestion phenomenon can be split into two pieces to explain the observed behavior of motorist. (1) on the one hand, we can identify a structural congestion, due to the physical conditions of the interaction process (vehicles-infrastructure). This congestion will be an increasing function depending on the density (in terms of vehicles on links) and other factors. (2) Apart from the structural effect (mostly modeled by previous static and dynamic approaches in different ways), we find a congestion that depends on the degree of externality observed among agents occupying the same infrastructure at the same time. This degree of externality can be explained as the degree of homogeneity among agents in terms of driving habits and behavior. The more similar are the motorists driving at the same time on a specific network arc, the more fluently the movement of vehicles as a homogeneous flow current, which should induce a lower degree of observed congestion. On the contrary, even though the physical conditions could make the network attractive to circulate at high speed limits, the interactions between very different type of drivers would cause too many interruptions resulting in bad conditions for the flow to move properly. One first advance in the modeling approach is through the recognition of these two different dimensions of traffic congestion to be considered separately in the mesoscopic formulation.

- The proposed approach is supported by a redefinition of the traditional Wardrop principle for traffic equilibrium. In this model, the choice set of routes (for each type of individual and for each O/D pair) will be restricted by the set of routes that are attractive to each group of homogeneous motorists, based on the expected travel time through such routes under free flow conditions. Note that each type of agent (with specific driving habits) will choose different routes according to conditions not appreciable without considering driving patterns differentiation.

At this stage, we have formulated a first mathematical model, built in order to further construct an equilibrium scheme able to identify the aspects presented in this document. The model constructed so far captures the dynamics in the transport process at a mesoscopic level (aggregation of individual vehicles but identifying platoons of vehicles of different types and density on arcs measures), where we individualize the behavior on arcs and nodes (representing arterials and intersections respectively, with special attributes for driving behavior at each case)

5. Linkages to other works in RHM

The works in RHM that can be related to this thesis work are two: the thesis work of Hector Lopez, student of the PhD in Engineering Systems at Universidad de Chile, and the work of Andreas Justen on travel demand modeling. Together, the three theses build up a multi-scale formulation of the urban system.

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