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Symbiotic network design strategies in the presence of coexisting transportation networks

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ABSTRACT

As urbanization increases and new business models for transportation and mobility arise, the design of transportation networks should no longer be done in a vacuum. Design interactions between multiple networks have largely been analyzed either as non-cooperative games with non-unique Nash equilibria, even if assumptions needed for such games are not satisfied, or using knowledge-based or agent-based methods that cannot explicitly quantify network sensitivities. A new framework is proposed to model network design in the presence of coexisting networks using multiobjective optimization in a novel manner to identify symbiotic relationships. The framework does not require strict assumptions about availability of information or timing of decisions, and it can be used to examine network sensitivities that knowledge-based methods cannot. A bundled discount pricing problem and subsidy problem are derived from the symbiotic relationships. The framework is applied to formulate a symbiotic bike-sharing network design problem in the presence of a coexisting transit system as a departure-time-elastic multicommodity flow problem. A small network example demonstrates the potential dependency between transit systems and bike-sharing systems for the first time, and the existence of an optimal discount value for considering bundled fares. A larger bike-sharing network, BIXI, is examined in the presence of the Toronto Transit Commission (TTC) in downtown Toronto to address the question of subsidy. It is found that BIXI is operating in a relatively transit-friendly state, and subsidy by TTC to maintain a status quo in Toronto may be worth considering if the cost of subsidy is less than a conservative average reduction achieved of 2.43 units of transit-only user cost for every 1 unit increase of bike-sharing cost.

1. Introduction

There is an increasing interest in supporting urban mobility with multimodal transport networks. The Government of Canada has invested over $5 billion in federal public transit-related infrastructure since 2000–2001, and has identified public transit as one of five national priorities under the Building Canada Fund (Transport Canada, 2012). However, decision support tools for designing and investing in multimodal transport systems tend to focus on single systems devoid of interaction with others. Conventional network design and optimization models assume that the network of interest operates in a vacuum, but this assumption is losing validity. For example, when a bike-sharing company like BIXI decides where to invest in new bike-sharing stations as they expand in Toronto, the pricing strategies of parking garages near the candidate locations will impact

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whether people choose to ride a bike to commute or to drive there. Locating a bike-sharing station near a public transit station may allow riders to link their subway and bike trips together. A chief question that is asked by policymakers is whether, and how much, a host transportation network should consider subsidizing the second network (Alcoba, 2013; Bateman, 2013).

There is ample evidence that public agencies and researchers recognize this need to consider network interactions in transit network design and planning, at least between competing or cooperating operators and decision-makers. Harker (1988) devised a generalized Nash equilibrium model in a private mass transit market to evaluate its feasibility in the United States. Yang and Woo (2000) formulated a competitive Nash equilibrium between two toll pricing firms, and Zhang et al. (2011) considered competitive, cooperative, and Stackelberg equilibrium conditions. Intercity transport competition between high speed rail and airlines has also been considered (Adler et al., 2010). Coordination between traffic management centers (e.g. Logi and Ritchie, 2002) is a known problem. In 2012, the Transportation Research Board at the U.S. National Academies created a $300 thousand (USD) request for proposals (TCRP H-49) for "Improving Transit Integration among Multiple Transit Providers". A more detailed literature review is presented in Section 2, but needless to say, there is a fairly long history to this literature that is garnering more interest from researchers and practitioners in recent years.

The interaction between two or more networks has generally been treated as a cooperative or non-cooperative game between network operators. While many instances should be treated as games with simultaneous decisions (Nash equilibria) or leader–follower decisions (Stackelberg equilibria), this assumption is not always true. Many transportation networks coexist, but may either operate (1) at different economies of scope, (2) at different strategic time horizons, or (3) with different functions or roles. The bike-sharing network and public transit network example is one case. In this scenario, the designs of one network impact the other since travelers can choose between the two networks or link trips with them. However, there is no zero-sum game being played. A private bike-sharing network may be designed to maximize profit or minimize operating costs while the public transit agency is concerned with public welfare. The functions and roles of the two networks are not the same; both transport people, but the bike-sharing network is designed for close distance trips. Third, the two networks operate at different time horizons and economies of scope. A bike-sharing network may be modified in one day by adding new bikes to a bike station with sufficient docks or relocating the docks altogether (Morency et al., 2011); new public transit vehicles would need to be procured over a longer time frame for a much higher cost.

There is a gap in a generalized methodology to analyze *coexisting networks* that do not necessarily operate under the assumptions of a strict Cournot–Nash or Stackelberg game. To date, no structure has been provided to evaluate the types of coexistence between any two transportation networks, the degree to which that coexistence can facilitate cooperation or competition, or any interaction opportunities or strategies.

Even scenarios that should be analyzed as games between multiple network operators can stand to benefit from a more generalized structure. The game-theoretic methods developed thus far have non-unique Nash equilibria, which may or may not be Pareto optimal. If we can make the reasonable assumption that coordination or repeated games (Kurz and Hart, 1982) are possible in transportation network design, then we can ignore non-Pareto optimal Nash equilibria altogether to relax the unilateral requirement and obtain stronger Pareto optimal Nash equilibria (PONE). By restricting to PONE and using a more generalized method to reach those equilibria, it is possible to gain more insights on interaction strategies between coexisting networks that could not be possible under the more restrictive game-theoretic methods.

We propose a new framework to analyze network design strategies in the presence of coexisting networks. This framework uses multiobjective optimization to represent the impacts of one decision-maker's strategies on another (e.g. Mordukhovich, 2004) in a context of symbiotic organisms to derive network design strategies. Symbiosis is a biological phenomenon that refers to the coexistence of two different living organisms that form persistent associations (Douglas, 2010). The coexistence leads to relationships between the two organisms that may be beneficial to both parties (mutualistic) or only to one party at the expense of the other (parasitic). In both cases, the organisms are not required to operate at the same strategic planning level that is assumed for game theory applicability, although it has been considered at an evolutionary scale (e.g. Renaud and de Meeüs, 1991). Examples of symbiosis in nature include sea anemones and hermit crabs; goby fish and snapping shrimp; African oxpeckers with many of the herd mammals like zebra, elephants, and hippopotamuses; ants and fungi; and of course, bees and orchids (McElroy, 2010).

In essence, symbiosis is a more general concept of interaction than game theory that is interpreted mathematically in this study with multiobjective optimization methods for the design and analysis of coexisting transportation networks. Examining coexisting networks under this perspective allows us to, for example, justify the amount of subsidy to give to another network, or to design coordinated network strategies like bundled fares to access multiple networks.

The remainder of this paper is organized as follows. Section 2 goes into greater depth with the literature and the motivation for why game theoretic methods are not generalized enough to address the types of problems involving coexisting networks. Section 3 introduces the proposed framework and two example symbiotic network design strategies that can be derived from it. Section 4 applies the framework to a representative problem: bike-sharing network design in the presence of a host public transit network, which also considers a new formulation for bike-sharing network design to allow for the interaction. Section 5 includes numerical tests with a small demonstration network and a realistic application with policy insights drawn from a case study of the BIXI bike-sharing network interacting with the Toronto Transit Commission (TTC) transit system.