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A marginal utility day-to-day traffic evolution model based on one-step strategic thinking

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ABSTRACT

Most deterministic day-to-day traffic evolution models, either in continuous-time or discrete-time space, have been formulated based on a fundamental assumption on driver route choice rationality where a driver seeks to maximize her/his marginal benefit defined as the difference between the perceived route costs. The notion of rationality entails the exploration of the marginal decision rule from economic theory, which states that a rational individual evaluates his/her marginal utility, defined as the difference between the marginal benefit and the marginal cost, of each incremental decision. Seeking to analyze the marginal decision rule in the modeling of deterministic day-to-day traffic evolution, this paper proposes a modeling framework which introduces a term to capture the marginal cost to the driver induced by route switching. The proposed framework enables to capture both benefit and cost associated with route changes. The marginal cost is then formulated upon the assumption that drivers are able to predict other drivers' responses to the current traffic conditions, which is adopted based on the notion of strategic thinking of rational players developed in behavior game theory. The marginal cost based on 1-step strategic thinking also describes the "shadow price" of shifting routes, which helps to explain the behavioral tendency of the driver perceiving the cost-sensitivity to link/route flows. After developing a formulation of the marginal utility day-to-day model, its theoretical properties are analyzed, including the invariance property, asymptotic stability, and relationship with the rational behavioral adjustment process.

1. Introduction

1.1. Motivation

Over the past 3 decades, a large number of day-to-day (DTD) traffic evolution models have been developed to represent how traffic flow evolves under disequilibrium. These DTD models describe drivers' individual route switching behavior, and the corresponding traffic pattern changes at an aggregate level. The traffic evolution processes characterized by these DTD models allow transportation planners and operational managers to evaluate the transportation network performance under disequilibrium and help them develop reliable network design and traffic control plans to respond to expected and unexpected transportation network disruptions. Existing DTD models can be classified in terms of whether they are constructed in continuous or discrete

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time space, and whether they capture the uncertainty in transportation systems (Watling, 1999). Reviews of DTD traffic evolution modeling can be found in Watling and Cantarella (2015).

Most deterministic DTD traffic evolution models, either in continuous-time or discrete-time space, have been formulated based on a fundamental assumption of driver route choice rationality; namely, drivers tend to switch to the routes with lower perceived travel costs. In this context, the difference in perceived travel costs can be viewed as the marginal benefit to the driver. The rate of route switching is then linked to the marginal benefit measured by the travel cost reduction. Hence, in the existing DTD models, the marginal benefit is the basis for a rational individual to switch to an alternative route because she/he perceives that the target route has a cost lower than her/his current one. In this sense, drivers stop route switching when they perceive that the marginal benefit is zero.

Modeling the marginal benefit in classical deterministic DTD traffic evolution models relies on an underlying assumption of "perfect knowledge" on the link/route costs. This implicitly assumes knowledge of the route decisions of other drivers and the link performance functions. The latter reflects that drivers perceive the link/route cost sensitivity to flow through their long-term travel experience, as discussed in Kumar and Peeta (2015). The explicit consideration of link/route cost sensitivity to flow illustrates a marginal cost to the driver that arises from the concurrent decisions of other drivers, which can reduce the anticipated marginal benefit for that driver. In economics, this type of cost represents the "shadow price" of route switching. This marginal cost in DTD traffic evolution context corresponds to the marginal cost in transportation economics, where an additional vehicle in traffic imposes a definite cost on all users (Mohring, 1976). In this context, a rational driver decides to switch to an alternative route on the next day because she/he perceives that the route cost reduction (i.e., marginal benefit) will be greater than the route cost increase due to the switched flow (i.e., the marginal cost). As the marginal cost is considered, other drivers' route switching behavior and the resulting traffic conditions impact rational drivers' route choice decisions. In the sense of marginal decision rule, drivers stop route switching when they perceive that the marginal benefit equals the marginal cost.

This paper introduces the marginal travel cost into the modeling of DTD traffic evolution, to enable consistency with the marginal decision rule that follows the economic principle that "rational people think at the margin" (Mankiw, 2012). It states that a rational individual evaluates his/her marginal utility, defined as the difference between the marginal benefit and the marginal cost, of each incremental decision. That is, both the marginal cost and the marginal benefit of each route switch need to be factored in the modeling of DTD traffic evolution. Hence, in this study we propose a conceptual shift in the definition of rationality by additionally introducing the notion of marginal cost rather than just the notion of marginal benefit considered in classical DTD models. The specification of the marginal cost in the proposed marginal utility DTD modeling framework may vary with the assumption on drivers' perception. This paper adopts the 1-step strategic thinking in behavioral game theory (Camerer, 2003) to derive an explicit formulation of the marginal cost, so that the analytical properties can be derived rigorously.

1.2. Literature review

The concept of rationality plays an important role in developing deterministic DTD models. Recently, Yang and Zhang (2009) focus on the behavioral rationality of deterministic DTD traffic evolution models. They note that most deterministic DTD evolution processes are rooted in deterministic user equilibrium (DUE), under which each driver cannot further reduce his/her travel cost by unilaterally switching to an alternative route (Wardrop, 1952). Their paper synthesizes the common characteristics of the proportional-switch adjustment process (Smith, 1983; Smith, 1984; Smith and Wisten, 1995; Huang and Lam, 2002; Peeta and Yang, 2003), network tâtonnement adjustment (Friesz et al., 1994), projected dynamical system (Zhang and Nagurney, 1996; Nagurney and Zhang, 1997) and evolutionary traffic dynamics (Sandholm, 2001; Yang, 2005). Yang and Zhang (2009) show that, under these traffic evolution processes, the route flow changes tend to reduce the aggregate travel cost given the previous day's route costs. They label these processes as rational behavior adjustment processes (RBAP), whose stationary link flow patterns satisfy the DUE. These RBAP are all established on route flows.

In contrast to the route-based models summarized in Yang and Zhang (2009), some recent studies have focused on developing deterministic DTD models based on link flows. These link-based DTD models adopt the same concept of rationality as route-based DTD models. He et al. (2010) point out that route-flow based models suffer the inherent shortcomings of route non-uniqueness and route overlap. A link-based DTD model is then developed, where traffic evolution is characterized by link flow dynamics. The link-based DTD model has been applied to study the traffic evolution after the I-35W Bridge collapse in Minneapolis, Minnesota (He and Liu, 2012). Recently, three approximation models have been developed by Wang et al. (2015) to improve the model transferability of the link-based DTD model. Smith and Mounce (2011) propose another link-based DTD model, where link flows are determined by the flow splitting rates at each node. The adjustment of the link flow splitting rate enables incorporating node-level controls into the traffic evolution model. He et al. (2015) extend Smith and Mounce's model by introducing a projection operator at the node level. Guo et al. (2013) extend the RBAP to the link level, and propose a discrete-time rational adjustment process. Guo et al. (2015) provide a general modeling framework for continuous-time link-based DTD models. They show that the existing link-based DTD models satisfy the continuous-time modeling framework. These link-based DTD models have the DUE flow as their stationary point.

A category of deterministic models that differs significantly from others is based on the boundedly rational (BR) choice behavior. In contrast to the rational behavior adjustment processes, the BR-DTD traffic evolution model assumes that drivers can take any route whose travel cost is within an "indifference band" of the shortest route cost. Thereby, its stationary link flows satisfy the boundedly rational user equilibrium (BRUE) instead of the DUE. Guo and Liu (2011) introduce bounded rationality into modeling DTD traffic evolution. The BR model is used to explain the phenomenon that the traffic state is not restored after