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On node models for high-dimensional road networks

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ABSTRACT

Macroscopic traffic models are necessary for simulation and study of traffic's complex macro-scale dynamics, and are often used by practitioners for road network planning, integrated corridor management, and other applications. These models have two parts: a link model, which describes traffic flow behavior on individual roads, and a node model, which describes behavior at road junctions. As the road networks under study become larger and more complex — nowadays often including arterial networks — the node model becomes more important. Despite their great importance to macroscopic models, however, only recently have node models had similar levels of attention as link models in the literature. This paper focuses on the first order node model and has two main contributions. First, we formalize the multi-commodity flow distribution at a junction as an optimization problem with all the necessary constraints. Most interesting here is the formalization of input flow priorities. Then, we discuss a very common "conservation of turning fractions" or "first-in-first-out" (FIFO) constraint, and how it often produces unrealistic spillback. This spillback occurs when, at a diverge, a queue develops for a movement that only a few lanes service, but FIFO requires that all lanes experience spillback from this queue. As we show, avoiding this unrealistic spillback while retaining FIFO in the node model requires complicated network topologies. Our second contribution is a "partial FIFO" mechanism that avoids this unrealistic spillback, and a (first-order) node model and solution algorithm that incorporates this mechanism. The partial FIFO mechanism is parameterized through intervals that describe how individual movements influence each other, can be intuitively described from physical lane geometry and turning movement rules, and allows tuning to describe a link as having anything between full FIFO and no FIFO. Excepting the FIFO constraint, the present node model also fits within the well-established "general class of first-order node models" for multi-commodity flows. Several illustrative examples are presented.

1. Introduction

Traffic simulation models are vital tools for traffic engineers and practitioners. As in other disciplines focusing on complex systems, such as climate or population dynamics, traffic models have helped to deepen our understanding of traffic behavior.

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They are widely used in transportation planning projects in which capital investments must be justified with simulation-based studies (CSM, 2015). Recently, with the increased interest in Integrated Corridor Management (ICM) and Decision Support Systems (DSS), traffic models have also found a new role in real-time operations management. In both the planning and ICM/DSS contexts, the models have steadily grown larger - such as highway plans that append adjacent arterial networks or managed lanes (Hadi et al., 2013) - and more complex - such as integration of new “smart” vehicle and communications technologies into real-time ICM.

Traffic models are typically divided into three categories based on their level of abstraction. At the most granular level, microscopic models simulate the motion and behavior of individual vehicles. At the other extreme, macroscopic models describe the evolution of traffic flows and buildup and breakdown of congestion along the lineal direction of a road in aggregate terms. Mesoscopic traffic models occupy the intermediate space. Of the three, the highly-abstracted macroscopic models unsurprisingly have the lowest computational cost, which makes them well-suited for study of large and complex networks of roads.

A macroscopic model is said to consist of a *link* model and a *node* model. A link model describes the evolution through time of the traffic flow along homogeneous sections of road. Several types of link models exist, such as those that give link flows as functions of link densities (e.g., the widely-used cell transmission model of Daganzo, 1994 and its descendants), those that track the vehicles only at link boundaries (Yperman et al., 2005), and others (see Nie and Zhang, 2005 for a broad overview). For the purposes of this paper, we do not specify a particular class of link model, but only require that the model describe, as a function of its state at time t, both the amount of vehicles trying to exit the link ($S(t)$, the link’s *demand*) and the amount of vehicles that the link is able to accept from upstream ($R(t)$, the link’s *supply*).

A traffic model may contain multiple classes of vehicles that share the road, and each class may have their own demands. Separate vehicle classes are often called *commodities*. In addition to the link and node models are the so-called *turning* or *split ratios*, which define the vehicles’ turning choice at the junction — the ratios of vehicles of each commodity that take each of the available movements. These split ratios might be measured, such as by manually counting flows of each movement at traffic intersections, estimated from some model, or prescribed by the modeler to make vehicles follow a certain path. In the context of this paper, we consider only the split ratios at particular junctions. Nodes join the links, and the node model computes the set of flows through a node for each commodity as a function of its incoming links’ demands and its outgoing links’ supplies.

Of course, while macroscopic models may be fast relative to more granular meso- and microscopic models, their computational needs are affected with the growth of network size and complexity. High computational cost can be exacerbated in modern ICM applications, as well. Many real-time traffic state estimation techniques follow an *ensemble method* approach, where many simulations describing different possible events are processed simultaneously (see e.g. Work et al., 2010; Wright and Horowitz, 2016). ICM decision-making can follow a similar approach, with multiple simulations being performed at a plan-evaluation step to project traffic outcomes under a range of possible future demands.

While the computational complexities stemming from links have been well-studied, node models can be sources of computational costs as well. These costs emerge when one models a network with many multi-input and/or multi-output junctions, or junctions where more than two links enter or exit. We adopt the term “high-dimensional” to describe these sorts of networks, to avoid ambiguity with similar terms such as “large,” which may also describe networks with many long roads and not many junctions. This paper draws on the authors’ experience in creating models for high-dimensional networks that describe a freeway, adjacent managed lanes (such as high-occupancy vehicle (HOV) lanes or tolled lanes), and/or the surrounding arterial grid for ICM purposes. We will discuss in Section 2.1 how modern node models can exacerbate computational complexity in high-dimensional networks by creating a trade-off between model accuracy and number of links; thankfully, this trade-off can be overcome in a simple manner, as we will detail in Section 3. Section 4 gives two examples, one being a slight modification of a well-studied example from Tampère et al. (2011), in which we demonstrate how our new node model considerations differ from previous node models in the junction-geometry information they consider and the flows produced. Appendix A summarizes the notation used in this paper.

2. Common node models and their drawbacks

2.1. Node models

The traffic node problem is defined on a junction of M input links, indexed by i, and N output links, indexed by j, with C vehicle commodities, indexed by c. As mentioned above, in first-order traffic models, the node model is said to consist of the mechanism by which, at time t, incoming links’ per-commodity demands $S_i^c(t)$, split ratios $\beta_{i,j}^c(t)$ (which define the portion of vehicles of commodity c in link i that wish to exit to link j), and outgoing links’ supplies $R_j(t)$ are resolved to produce throughflows $f_{i,j}^c(t)$. Nodes are generally infinitesimally small and have no storage, so all the flow that enters the node at time t must exit at time t. To simplify the notation, in the remainder of this paper we consider the node model evaluation in each time instant as an isolated problem (as we are assuming no storage), and omit the variable t for these quantities.

The node problem’s history begins with the original formulation of discretized first-order traffic flow models (Daganzo, 1995). There have been many developments in the node model theory since, but we will reflect only on some more recent results.