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Link-based system optimum dynamic traffic assignment problems with environmental objectives

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ABSTRACT

Maintaining air-quality standards has been a priority for transportation planners and policy makers worldwide. However, most existing system optimum dynamic traffic assignment (SO-DTA) models do not accommodate environmental objectives. In this paper, we use the link transmission model (LTM) to develop SO-DTA models that minimize total system emissions (TSE) in single destination networks. We use step functions to approximate cumulative flow curves for individual links, and to decompose link inflow into sub-flows according to time intervals at which they leave the link. The decomposed link inflows are used to estimate link emissions. Dynamic network constraints, non-vehicle holding constraints and link inflow decomposition constraints are considered, and SO-DTA problems with environmental objectives are formulated as mixed integer linear programming (MILP) problems. Any average speed based emission functions can be used for our models. Finally, numerical examples are provided to demonstrate the performance of the proposed models.

Introduction

Dynamic traffic assignment (DTA) has long been recognized as a key component of network planning and transport policy evaluation, in addition to real-time traffic operation and management (Szeto and Lo, 2006). System-optimum DTA (SO-DTA), a special case of DTA based on a dynamic extension of Wardrop's (1952) second principle, is used to predict a time-dependent traffic state with optimal network performance, and to provide a benchmark for controlling and managing dynamic traffic networks. For example, SO-DTA models are used in road congestion pricing (e.g., Yang and Meng, 1998; Carey and Watling, 2012), signal control (e.g., Lo, 2001; Lin and Wang, 2004), network design (e.g., Waller and Ziliaskopoulos, 2001; Waller et al., 2006), and emergency evacuation traffic management (e.g., Liu et al., 2006; Chiu et al., 2007).

Existing SO-DTA models can be classified into continuous-time models (e.g., Friesz et al., 1989; Chow, 2007, 2009a, 2009b; Ma et al., 2014, 2015) and discrete-time models (e.g., Merchant and Nemhauser, 1978a, 1978b; Carey, 1987; Ziliaskopoulos, 2000; Nie, 2011; Zheng and Chiu, 2011; Long and Szeto, 2015), depending on whether the modeling period is discretized into many time steps. Both categories of model have advantages and disadvantages. Continuous-time models can provide analytical insights (such as the closed form externality analysis), but cannot be efficiently solved due to their complex structure (Nie, 2011). Discrete-time models are usually formulated as mathematical programming problems, such as linear programming (LP) problems (e.g., Ziliaskopoulos, 2000) and mixed integer linear programming (MILP) problems

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(e.g., Lin and Wang, 2004; Pavlis and Recker, 2009), and can thus be more easily solved than continuous-time SO-DTA models. However, this category of models also compromise computational tractability in large-scale network applications due to the presence of numerous decision variables and constraints.

There are three major types of objectives in existing SO-DTA models: minimizing total system travel time (TSTT) (e.g., Merchant and Nemhauser, 1978a, 1978b; Carey, 1987; Ghali and Smith, 1995; Ziliaskopoulos, 2000; Li et al., 2003; Lin and Wang, 2004; Munoz and Laval, 2006; Shen et al., 2007; Chow, 2007, 2009a, 2009b; Pavlis and Recker, 2009; Nie, 2011; Zheng and Chiu, 2011; Zhu and Ukkusuri, 2013; Ma et al., 2014; Mesa-Arango and Ukkusuri, 2014; Long and Szeto, 2015; Zheng et al., 2015), minimizing total system emissions (TSE) (e.g., Aziz and Ukkusuri, 2012), and minimizing both TSTT and TSE for a whole network in an integrated manner (e.g., Aziz and Ukkusuri, 2012; Ma et al., 2015). Most existing SO-DTA models accommodate only network mobility, and are used to meet the first of the above objectives: to minimize the TSTT spent by travelers in a network. SO-DTA models designed to address TSTT are usually based on linear or convex functions of link flow. This leads to mathematical programming formulations that are computationally efficient and solvable for reasonably sized networks. The objective of minimizing TSE has long been integrated with static traffic assignment problems (e.g., Rilett and Benedek, 1994; Benedek and Rilett, 1998; Nagurney, 2000; Yin and Lawphongpanich, 2006). However, few researchers have considered SO-DTA problems in terms of TSE. To the best of our knowledge, Aziz and Ukkusuri (2012) were the first to propose a SO-DTA model with an environmental objective. Aziz and Ukkusuri (2012) integrated an emissions-based objective with a traditional SO-DTA framework, and formulated the SO-DTA problem in terms of TSE as a nonlinear and non-convex mathematical function. The proposed model was further approximated by quadratic programming (QP) model. However, the accuracy of the approximation is only high when the network is very congested, and the model is limited to a particular carbon monoxide (CO) emission function. To address the third objective, SO-DTA models are developed with weighted TSTT and TSE components and capture the trade-off between emissions and travel time (e.g., Aziz and Ukkusuri, 2012; Ma et al., 2015).

Dynamic network constraints are generally used to formulate feasible domains for existing SO-DTA models. There are four categories of dynamic network constraints: mass balance constraints, flow conservation constraints, flow propagation constraints, and definitional constraints. The constraints used are highly dependent on the underlying DNL model, such as point queue models (Ban et al., 2008, 2012; Long et al., 2015b; Ren et al., 2016), exit flow models (e.g., Merchant and Nemhauser, 1978a, 1978b; Carey and Srinivasan, 1993; Lam and Huang, 1995; Wie and Tobin, 2002), and advanced exit flow models (e.g., Kuwahara and Akamatsu, 2001; Lo and Szeto, 2002; Yperman, 2007; Nie, 2011; Meng and Khoo, 2012; Long et al., 2013b, 2015a, 2016; Zheng et al., 2015; Han et al., 2015a, 2015b). The traffic flow models used in DTA problems should also have certain desirable properties, such as queue spillback (e.g., Daganzo, 1995; Lo and Szeto, 2002; Szeto and Lo, 2004; Ma et al., 2014; Chow et al., 2015; Stewart and Ge, 2015; Han et al., 2016; Jiang et al., 2016), first-in-first-out (FIFO) (e.g., Astarita, 1996; Huang and Lam, 2002; Long and Szeto, 2015), and non-vehicle holding (NVH) (e.g., Ziliaskopoulos, 2000; Shen et al., 2007; Nie, 2011; Zheng and Chiu, 2011; Zhu and Ukkusuri, 2013). Queue spillback occurs when the end of a queue spills backward in the network. This property can be easily captured in a SO-DTA model by incorporating a physical queue traffic flow model. FIFO implies that vehicles that enter a link earlier will leave it sooner (Wu et al., 1998; Lo and Szeto, 2002; Long et al., 2011). The FIFO constraint on traffic flow in a single-destination network is usually assumed to be satisfied by nature, and the constraint becomes necessary when multi-commodity flow is addressed. Vehicle holding (VH) implies that drivers are reluctant to move forward from upstream links to downstream links even if there are vacant spaces in the downstream links. In many discrete-time SO-DTA models, the problem of VH stems from relaxation and linearization (e.g., Merchant and Nemhauser, 1978a; Carey and Subrahmanian, 2000; Ziliaskopoulos, 2000; Nie, 2011).

In this paper, we use step functions to approximate a cumulative-flow curve for each link, and decompose link inflow into sub-flows according to time of departure from the link. Based on the travel times estimated from the decomposed link inflows, we develop two methods of evaluating link emissions. In contrast with existing methods (e.g., Aziz and Ukkusuri, 2012; Ma et al., 2015), the proposed methods of estimating link emissions can be integrated with any average speed based emission functions. In addition, we use Yperman's (2007) link transmission model (LTM) to represent dynamic network constraints and NVH constraints on SO-DTA problems in single-destination networks. The LTM combines Daganzo's (1995) cell transmission model (CTM) with a triangular fundamental diagram and Newell's (1993) cumulative curves. As each link can be treated as a single cell, the LTM has a much higher computational efficiency than the Lighthill-Whitham-Richards model, a classical numerical solution scheme, while retaining the latter's accuracy (Yperman, 2007). We also develop link inflow decomposition constraints to represent the relationship between cumulative decomposed link flow and cumulative link inflow and outflow. Integrating the LTM-based dynamic network constraints, NVH constraints, link inflow decomposition constraints and TSE derived from the estimated link emissions, we formulate SO-DTA models with environmental objectives as MILP problems. Four SO-DTA models are proposed. Two of them are with single objective, and the other two models are with bi-objective.

The main contributions made in our research are as follows.

First, we develop a novel method of estimating link emissions and TSE using decomposed link inflow. The TSE obtained is a linear function with respect to cumulative link flow.

Second, we propose link inflow decomposition constraints for SO-DTA problems with environmental objectives, which represent the relationship between cumulative decomposed link inflow and cumulative link inflow and outflow.

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