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Emission Modeling and Pricing in Dynamic Traffic Networks

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Abstract

This paper proposes an emission pricing model for dynamic traffic networks with single destinations. The model contains two sub-problems: a system optimum dynamic traffic assignment problem and a first-best dynamic emission pricing scheme. It proves that under certain conditions, there exists a free-flow optimal solution to minimize the generalized system cost including total travel times and total emissions. The optimal first-best emission pricing can then be determined by solving an optimal control problem, using the free-flow dynamic system optimal solution as the input. Numerical results are provided to illustrate the proposed model and its solution method.

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Keywords: emission pricing; dynamic system optimum; free-flow optimal solution; dynamic user equilibrium; first-best pricing

1. Introduction and Motivation

Air pollution has been recognized as acute negative effects in many urban areas. Recently, some major urban areas in Eastern Asia have to face reduced visibility and deteriorated air quality frequently, largely due to emissions (such as smug) from industry and urban traffic. Reducing the emissions from urban traffic becomes necessary and urgent for a sustainable urban environment. Traffic emission programs and regulations on vehicle population and emission rates have been implemented by many regions in the last decades (Netherlands Ministry of Housing, Spatial Planning, and the Environment (2004); Fung et al. (2010)). However, the objective to reduce air pollution has not been fully achieved by these programs alone. Besides government regulations, market-based approaches for network-wide emission control have been proposed and studied recently.

As introduced in the marginal cost pricing theory in Pigou (1920) and its later developments in Walters (1961); Vichrey (1969), road pricing has been recognized as a key market-based approach to efficiently internalize the external costs imposed by the drivers on other users in the network, and to maximize the total social welfare. As a special form of road pricing, network-wide emission pricing aims at the pricing of the emission externalities in traffic networks to minimize the total externalities, including the environmental costs.

Emission pricing studies on different objectives have been performed in the recent decades. Some emission pricing models considered traffic emissions as the single indicator for the externalities (see Yin and Lu (1999); Hizir (2006);

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Sharma and Mishra (2011)), while more and more studies simultaneously incorporated the system time costs, e.g., travel and waiting times, in addition to the environmental costs, into the emission pricing model. To achieve the system optimal cost including both time and environmental costs, Johansson (1997) suggested that both the congestion effects and the environmental externalities should be considered.

There are generally two approaches to balance the trade-off between time and environmental costs. One approach is to embed side constraints in the models, such as environmental capacity constraints in Xu et al. (2013); Zhong et al. (2012); Li et al. (2012). The other approach is to propose multi-objective formulations in terms of the weighted sum method (Yin and Lawphongpanich (2006); Abou-Zeid (2003); Qiu and Chen (2007); Ferguson et al. (2010); Szeto et al. (2014)), so that both types of costs are combined as a single objective. Yin and Lawphongpanich (2006) showed that Pareto solution sets can be constructed by solutions with varied weights of such two types of costs. Other studies incorporated more dimensions such as social costs into the objective functions; see a comprehensive review in Szeto et al. (2012). Most of the previous studies on network-wide emission pricing focused on static traffic networks, with a few exceptions in Zhong et al. (2012); Friesz et al. (2013); Kickhöfer and Nagel (2013).

Similar to the congestion pricing problems, network-wide emission pricing can be broadly categorized as first-best pricing and second-best pricing. The former assumes that prices (or tolls) can be imposed on any location (e.g., links) of the network at any time, while the latter assumes that prices can only be imposed on a selected list of locations in the network or during a particular time period. It is well known that the second-best pricing can be formulated and solved as bi-level problems; see Yang and Bell (1997), Patriksson and Rockafellar (2002), Clegg et al. (2001), Liu and Boyce (2002), Abou-Zeid (2003) and Szeto et al. (2013) for static problems and Ban and Liu (2009); Friesz et al. (2007) for dynamic problems. First-best pricing for static networks can be modeled as marginal cost problems and solved accordingly, see Yang and Huang (2005). Such marginal cost approach however becomes complicated when applying to dynamic networks mainly because the traffic dynamics (such as flow propagation over time and space) introduce extra terms (such as the terms accounting for inter-temporal effects, see Carey and Srinivasan (1993); Shen et al. (2007)) in the marginal cost formulation that makes the marginal cost much harder to compute. However, considering road pricing on dynamic networks is more realistic because time-varying tolls can be implemented to achieve a better network performance and more realistic travel behavior by considering traffic dynamics in the modeling framework. More importantly, Lo and Szeto (2005) showed that the static and dynamic modeling approaches can produce diametrically opposite results. They found that the impacts of pricing policies under the static approach could be ill-represented. In some cases, the pricing schemes such determined could actually worsen the congestion problem. This finding illustrates the importance of adopting the dynamic modeling approach for pricing, albeit it is more complex and computationally more demanding than the static modeling approach.

Table A.1 in Appendix A summarizes the literature on dynamic road pricing, from which we can conclude the following. First, most studies mainly focused on congestion pricing whereas only in the last a few years, a handful studies considered emissions externalities when setting optimal prices. Second, the travel choice dimensions considered varied from one study to another, but for those studying emission pricing, at least two types of choices were considered. Third, both first and second best pricing have been examined in the literature, including those considering emission externalities. Second-best pricing seems to be more realistic and practical at the first sight, because not all links are allowed to charge a toll due to various physical or political constraints. However, with the recent emerging technologies, such as mobile sensing (Herrera et al., 2009; Ban et al., 2009; Ban and Gruteser, 2012) and connected vehicles (RITA, 2014), it is possible that each vehicle in the near future can be equipped with a tracking device so that, at least in principle, it can be charged a toll anywhere at any time if needed (assuming other related issues such as privacy and security can be properly addressed). This will make the first-best pricing idea feasible and probably more appealing. Moreover, although using microsimulation models may give better estimates of emissions, the analytical model presented in this paper allows more analyses of the model properties and thus provides useful insight about how to design and implement emission pricing schemes.

In this paper, we focus on the first-best emission pricing on a dynamic traffic network. We aim to develop a modeling framework to determine the optimal dynamic pricing schemes for all links of the network so as to minimize the generalized system costs, including total travel times and emission costs. The formulation is link-node as in Ban et al. (2008, 2012b), which avoids the use of path-specific variables. The optimization objective function in the proposed model incorporates both the economic and environmental externalities. More specifically, the economic externalities refer to the total travel and waiting time costs, while the environmental externalities refer to the total