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Marginal cost congestion pricing based on the network fundamental diagram

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A B S T R A C T

Congestion pricing schemes have been traditionally derived based on analytical representations of travel demand and traffic flows, such as in bottleneck models. A major limitation of these models, especially when applied to urban networks, is the inconsistency with traffic dynamics and related phenomena such as hysteresis and the capacity drop. In this study we propose a new method to derive time-varying tolling schemes using the concept of the Network Fundamental Diagram (NFD). The adopted method is based on marginal cost pricing, while it also enables to account realistically for the dynamics of large and heterogeneous traffic networks. We derive two alternative cordon tolls using network-aggregated traffic flow conditions: a step toll that neglects the spatial distribution of traffic by simply associating the marginal costs of any decrease in production within the NFD to the surplus of traffic; and a step toll that explicitly accounts for how network performance is also influenced by the spatial variance in a 3D-NFD. This pricing framework is implemented in the agent-based simulation model MATSim and applied to a case study of the city of Zurich. The tolling schemes are compared with a uniform toll, and they highlight how the inhomogeneous distribution of traffic may compromise the effectiveness of cordon tolls.

1. Introduction

The NFD extends the concept of the Fundamental Diagram (FD) and it expresses the aggregated flow along all the links in the network (production or flow) and the total number of vehicles in the network (accumulation or density) by means of a concave function. Like in the FD, the free-flow regime and congested regime can be identified respectively on the left branch and right branch of the diagram, while the region characterized by slower increase of production until capacity is reached is typically referred to as capacity regime.

Although the concept of network traffic relations can be traced back to the 1960s (Smeed, 1966; Wardrop, 1968; Godfrey, 1969) and further developed during the 1970s and 1980s (Zahavi, 1972; Mahmassani et al., 1984), only recently the existence of an invariant macroscopic relation between network average flow, average density and average speed has been confirmed and formalized by Daganzo (2007), Geroliminis and Daganzo (2007, 2008) and Daganzo and Geroliminis (2008). The NFD (also referred to as Macroscopic Fundamental Diagram) considerably eases the understanding of complex traffic phenomena and the implementation of effective traffic management measures. For this reason the body of literature on theoretical insights and applications of the NFD has been growing rapidly.

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Perhaps the most important theoretical finding consists of the influence of inhomogeneous conditions of traffic on the performance of the network. It is claimed in these studies that a well-defined NFD applies under specific ''regularity conditions'' concerning the homogeneity of links and the possibility of reaching the Wardrop Equilibrium. On the contrary, as a result of the uneven distribution of congestion the NFD shows scatter and hysteresis loops occur in the NFD diagram (Buisson and Ladier, 2009; Mazloumian et al., 2010; Geroliminis and Sun, 2011a,b; Gayah and Daganzo, 2011; Saberi and Mahmassani, 2012). With regard to this issue, a recent contribution came from Knoop and Hoogendoorn (2013) who quantified the effect of spatial distribution (also termed ''spread'') of congestion on the performance of a freeway network by means of a generalized NFD (gNFD).

At an applied level, other studies have utilized the concept of NFD to derive efficient strategies for travel demand and traffic control. For the topic of this paper, the most relevant applications are on the development of perimeter control-gating measures (Keyvan-Ekbatani et al., 2012, 2013; Geroliminis et al., 2013), routing strategies (Knoop et al., 2012), motorway management (Chow, 2015) and congestion pricing schemes (Geroliminis and Levinson, 2009; Zheng et al., 2012; Gonzales and Daganzo, 2012). In particular, the application of a macroscopic representation of network traffic conditions to the design of congestion pricing models represents a valuable approach to overcome some limitations of the traditional analytical congestion pricing schemes. Above all, the description of the supply curve (representing the cost related to the traffic volume) as a function of the network demand is consistent with the dynamic properties of traffic that are characterized by a drop of traffic throughput when the flow exceeds the capacity.

In this paper we address the design of cordon-based congestion pricing schemes based on macroscopic traffic variables. Above all, we discuss how the NFD and its generalizations can in various ways be used to compute fixed and variable congestion tolls that are consistent with the economical theory of marginal cost pricing. To this end we first discuss the way in which the spatial distribution of congestion influences the performance of a large urban network, here tested by means of agent-based simulations. Based on these findings, we propose two new methods to derive time-varying tolling schemes based on the NFD and its extension, a three dimensional NFD (3D-NFD) accounting for the effect of spatial spread. The first step toll depends on the marginal cost of a surplus of traffic inside the cordon area associated to the aggregated delay identified on the NFD. The second step toll avoids tolling drivers for travel time delays that are due to (uncontrolled) increases in the spatial spread of accumulation inside the cordon area. For the latter, we derive a 3D-NFD and fit a polynomial plane to quantify the extent of decrease of production determined respectively by the increase of accumulation and the deviation of spread from its natural increase. The two tolling schemes are finally evaluated on traffic flow performance indicators and compared with a uniform toll that operates the system at capacity by means of an offline iterative control.

In the first part of this study we will analyze the macroscopic traffic characteristics of the city of Zurich with the agent-based simulator MATSim (www.matsim.org), a state-of-the-art multi-agent model developed jointly by ETH Zurich and TU Berlin. In order to verify the appropriateness of using an agent-based approach to study, the main physical properties of traffic are tested. Since the boundaries of cordon-tolls are naturally defined by the existing constraints of the road network (ring roads or bridges) rather than by network partitioning techniques (Ji and Geroliminis, 2012), the area investigated will be likely characterized by heterogeneous conditions. For this reason, before designing the tolling schemes we will investigate dynamic features of the network-wide traffic, including the instability due to the presence of clusters of congestion, its relationship with scatter in the NFD and the hysteresis phenomena. In particular, we seek for additional evidence that even for low values of density, the traffic performance is compromised by unevenly distributed traffic. Based on these analyses we will investigate the relation between accumulation and spatial spread of traffic and finally derive a 3D-NFD that includes the deviation from the natural increase of spread as an additional dimension in order to consider the unstable conditions of the traditional aggregation–production relation. Along the same lines of Knoop and Hoogendoorn (2013), this approach is intended to represent an approach to deal with large heterogeneous networks, as alternative to the practice of network partition.

Subsequently we apply our findings about macroscopic properties of the (heterogeneous) network to derive two time-varying congestion-pricing schemes within MATSim. The following study aims at extending the approach by Zheng et al. (2012), who developed a uniform toll (Flat Toll) controlled by the NFD through an ''offline'' feedback control process. We do this by introducing an analytical derivation of the levels of charge based on the marginal cost of surplus of traffic in the cordon. The main rationale is to design a methodologically sound and tractable model consistent with both the economic (Pigouvian tax) and engineering (network-wide macroscopic modeling) theories. Hence, we propose two different cordon-based tolls: a time-varying toll that changes in discrete time-intervals (Step Toll); and a time-varying toll that explicitly accounts for the property of spatial distribution of congestion (Hybrid Toll). The effects of these two schemes are finally compared to those derived from the Flat Toll by means of a series of performance indicators.

The agent-based model MATSim has been adopted in this study because it allows high levels of realism of the pricing model in terms of users' heterogeneous route, mode and departure time decisions in large-scale complex road networks with several thousand agents. Furthermore, thanks to its high level of disaggregation it is possible to investigate more in depth issues such as distributional impacts of congestion pricing schemes (Kickhöfer et al., 2011). Additional applications of MATSim are described at www.matsim.org.

This paper is organized as follows. Section 2 describes the derivation of aggregated traffic flow properties in the urban road network of Zurich by means of the agent-based model MATSim. In Section 3 the effects of spatial distribution of congestion and the relation between accumulation and spatial spread of density are investigated. Sections 4 and 5 describe the design of three alternative congestion-pricing schemes controlled by the NFD and 3D-NFD and analyze their impacts on