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Air pollution dynamics and the need for temporally differentiated road pricing

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ABSTRACT

In this paper we investigate the effects of the temporal variation of pollution dispersion, traffic flows and vehicular emissions on pollution concentration and illustrate the need for temporally differentiated road pricing through an application to the case of the congestion charge in Stockholm, Sweden. By accounting explicitly for the role of pollution dispersion on optimal road pricing, we allow for a more comprehensive view of the economy–ecology interactions at stake, showing that price differentiation is an optimal response to the physical environment. Most congestion charges in place incorporate price bands to mitigate congestion. Our analysis indicates that, to ensure compliance with air quality standards, such price variations should also be a response to limited pollution dispersion.

1. Introduction

Air pollution from road transportation and its health impacts are considered to be among the most important challenges facing sustainable development in many places around the world (WHO, 2005). For instance, it is estimated that, just in Europe, exposure to urban pollution will cause a loss of 210 million life-years and 18,000 premature deaths in 2030, and that a significant fraction of these deaths and a range of other adverse effects on health are attributable to transport-related air pollution (IIASA 2012 and WHO 2013).

Though most studies of urban road pricing have focused on its role in relieving congestion, attention has recently turned toward using road pricing as an instrument to improve air quality (Verhoef, 2000; Small and Yan, 2001; Anas and Lindsey, 2011 and Chen and Yang, 2012). So far, pricing schemes have been proposed and applied in many cities worldwide, as for instance, Singapore, London and Stockholm. Empirical evaluations indicate that the environmental effects of road pricing are significant. For instance, Daniel and Bekka (2000) simulate the effects of road pricing on emissions of carbon monoxide (CO), nitrogen oxide (NO_x) and hydrocarbons (HC) for the New Castle County highway network in Delaware, United States. Their results indicate that vehicle emissions decrease as much as 30% in highly congested areas. Similarly, Beevers and Carslaw (2005) analyze the effect of the London congestion pricing scheme, indicating that the scheme brought a significant reduction in the emissions of NO_X and particulate matter (PM_{10}) due to an increased vehicle speed. Furthermore, the scheme brought a significant reduction in emissions of CO_2 (almost 20%) providing evidence that congestion pricing can assist governments in attaining climate change targets. Johansson et al. (2009) estimate that congestion pricing in central Stockholm

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has significantly reduced traffic emissions of NO_X and particles; however, the reduction in traffic emissions along the most densely trafficked streets was not sufficient for compliance with air quality standards.

Epidemiological studies have shown an approximately linear increase in health risk with increasing exposure to urban air pollutants like particulate matter, with no demonstrable threshold below which no effects are quantifiable. High spikes of pollution – rather than prolonged lower-level exposure – impose, however, the largest health hazards for those with impaired respiratory systems (Heal et al., 2012, page 6613 and WHO 2005). Road pricing can play an important role in reducing traffic flows and spreading the peaks of traffic, and by this means, reducing and smoothing the release of emissions of several pollutants over time. Nevertheless, air quality does not only depend on the emission rates of pollutants, but also on the assimilative capacity of the environment. This is defined as the capacity of an environment to cleanse itself after receiving a given level of emissions, by degrading or dispersing the emissions and converting them into substances that are harmless to humans or ecosystems (Pearce and Turner, 1990, p. 38). In the case of urban air pollution, the assimilative capacity is mainly driven by the meteorological factors (as wind speed, vertical temperature stratification, and mixing height) that govern air mixing and thus dispersion of locally emitted pollutants. Due to the large temporal variation of these meteorological factors, there is a strong average diurnal variation in the assimilative capacity, in addition to the variation in hourly traffic flows and consequently vehicular emissions (Hayas et al., 1981; Viana et al., 2005; Mikhailuta et al., 2009; Toth et al., 2011 and Kim et al., 2012). Furthermore, there is a strong day-to-day variation in assimilative capacity depending on weather patterns, such as anticyclonic conditions often having lower wind speeds than cyclonic weather conditions.

In this paper we investigate the effects of the temporal variation of the assimilative capacity on pollution concentration and illustrate the need for temporally differentiated road pricing through an application to the case of the congestion charge in Stockholm, Sweden. To the best of our knowledge, this is the first study analyzing how the variation in air mixing and pollution dispersion should be accounted for in road pricing. Our study provides a more comprehensive view of the economy–ecology interactions at stake, showing that price differentiation is an optimal response to the physical environment; higher charges at a certain time of the day are optimal since they discourage traffic when the assimilative capacity is constrained. Furthermore, our analysis provides some practical policy insights. Most congestion charges in place do resemble variable price schemes to some extent as they incorporate price bands to mitigate congestion.[1] Our analysis indicates that such price variations should also be a response to limited air mixing resulting in reduced assimilative capacity.

It is worth noticing that one could achieve reductions in traffic flows and pollution concentration by means of other policy instruments, as for instance, fuel taxes. However, several studies have shown (see for instance, Parry, 2002; Parry et al., 2007) that gasoline taxes (which raise the cost of all driving regardless of where the driving occurs or what time of the day) are an extremely blunt instrument for reducing traffic congestion, which varies enormously across urban and rural roads and between peak and off-peak driving times. Parry (2002) compares, for instance, the efficiency of congestion pricing versus gasoline taxation, showing that under a wide range of parameter scenarios the efficiency gains generated by congestion charges are at least three times as large as the efficiency gains under gasoline taxes. Time-varying congestion charges offer a more cost-effective means of reducing congestion since – unlike gasoline taxes – they would encourage people to drive a little earlier or later to avoid the peak of the rush hour as well as encouraging people to use less congested routes. Furthermore, a reduction in the incentives to drive during peak periods will also reduce the demand for additional capacity. Over time congestion charges may also encourage shops and businesses to relocate outside the congestion charge zone. The advent of wider use of electronic toll collection has also reduced the cost of implementing road pricing, increasing its cost efficiency.[2]

This paper is organized as follows. Section 2 describes general patterns of air pollution in some cities around the world. Section 3 introduces a congestion charge that takes into account the role and dynamics of the assimilative capacity in Stockholm (Sweden), where a congestion charge was introduced as a trial in 2006 and permanently in 2007. We start out from the scheme currently in place and look for modifications that would be consistent with the air quality standards (hereinafter AQSs) for nitrogen dioxide (NO_2) and particulate matter (PM_{10}) concentrations (hereinafter denoted as $[NO_2]$ and $[PM_{10}]$) and the meteorological factors that govern air mixing and dispersion of air pollutants through the day. Finally, Section 4 discusses the main results and concludes the paper.

2. Temporal variation of air pollution and assimilative capacity

Understanding urban air pollution due to road transportation is complex because several factors affect pollutants' dynamics and air quality. Air pollution levels from road transportation depend on polluters' type and number, meteorology,

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[1] Congestion charges can be classified as uniform (charge is constant over the entire application period), quasi-uniform (charge is constant over a specific time period and zero otherwise) and variable (charge is time-varying). See Wie and Tobin, 1998 and Joksimovic et al., 2005 for further discussion.

[2] The fact that temporally varying externalities are better addressed by instruments that follow the variation of damages (and hence, the variation in the externality) is well established in the literature in environmental economics. A clear example is the economics of controlling stock pollutants and climate change policy. If the regulator wants to implement an abatement strategy that minimizes the present value of all emission-related costs of the pollutant, he will have to take into account the decay rate of pollution and the dynamics of the stock of pollution when deciding the level of stringency of the regulation, which should also increase over time (see for instance, Hoel and Karp, 2002 and Moslener and Requate, 2007). Moreover, Coria (2011) discusses a series of actual examples where the stringency of environmental regulations in place is significantly increased to account for the variability in the assimilate capabilities of the environment, which poses difficult problems for pollution control policies (see also Bawa, 1975).