UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

WORKING PAPERS IN ECONOMICS

No 572

Air Pollution Dynamics and the Need for Temporally Differentiated Road Pricing

by

Jessica Coria, Jorge Bonilla, Maria Grundström and Håkan Pleijel

September 2013

ISSN 1403-2473 (print)
ISSN 1403-2465 (online)

Department of Economics
School of Business, Economics and Law at University of Gothenburg
Vasagatan 1, PO Box 640, SE 405 30 Göteborg, Sweden
+46 31 786 0000, +46 31 786 1326 (fax)
www.handels.gu.se info@handels.gu.se

Air Pollution Dynamics and the Need for Temporally Differentiated Road Pricing

Jessica Coria[(a)], Jorge Bonilla[(b)], Maria Grundström[(c)], and Håkan Pleijel[(c)]

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 bans 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.

Keywords: Air Pollution, Road Transportation, Road Pricing, Assimilative Capacity.

JEL Codes: L91, Q53, R48

[(a)] Corresponding author: Jessica Coria, Department of Economics, University of Gothenburg, P.O. Box 640, SE 405 30 Gothenburg, Sweden. Email: Jessica.Coria@economics.gu.se.
[(b)] Department of Economics, University of Gothenburg and Universidad de Los Andes, Bogotá, Colombia. Email: jobonill@uniandes.edu.co
[(c)] Department of Biological and Environmental Sciences, University of Gothenburg, Sweden. Emails: Maria.grundstrom@bioenv.gu.se, and Hakan.pleijel@bioenv.gu.se.
Financial support from the Biodiversity Ecosystems and Climate Change Program (BECC) to the Environmental Economics Unit and to the Department of Biological and Environmental Sciences at the University of Gothenburg is gratefully acknowledged. Jessica Coria gratefully acknowledges funding from the Sustainable Transport Initiative at the University of Gothenburg and Chalmers University of Technology. Jorge Bonilla gratefully acknowledges funding from the Swedish International Development Cooperation Agency (SIDA) and Universidad de los Andes. We are grateful to Olof Johansson-Stenman, Fredrik Carlsson, Anna Nagurney, Allen Blackman and Gunnar Eskeland for useful comments and suggestions. We also thank useful comments by seminar participants at the University of Gothenburg, Gothenburg Atmospheric Science Centre and Resources for the Future (Washington DC).

I. 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).

Road pricing is considered to be an effective way of reducing vehicular emissions. Up to date, pricing schemes have been proposed and applied in many cities worldwide, as for instance, Singapore, London and Stockholm. Though road pricing can play an important role reducing traffic flows, the possibility of reducing emissions 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 determined level of emissions, by degrading or dispersing the emissions and converting them into substances that are harmless to humans or ecosystems. In the case of urban air pollution, the assimilative capacity is mainly driven by the meteorological factors that govern air mixing and thus dispersion of the pollutants. Due to the large temporal variation of these meteorological factors, there is a strong day-to-day and diurnal variation in the assimilative capacity, in addition to the variation in hourly traffic flows and vehicular emissions (Hayas et al. 1981, Viana et al. 2005, Mikhailuta et al. 2009, Toth et al. 2011 and Kim et al. 2012).

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. Most previous studies of urban road pricing have focused on its role in relieving congestion. Only recently, attention has 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). Regarding optimal environmental road pricing[1,2], perhaps the most closely

[1] Previous studies have investigated optimal road pricing under demand and capacity fluctuations (See for instance Yildirim and Hearn 2005). Furthermore, the rarity of state-dependent pricing has been rationalized in multiple contexts, including situations where infrastructure and operating costs are (still) too high for it to be cost-effective (See for instance Levinson and Odlyzko 2008) as well as loss aversion with respect to tolls and usage conditions (Lindsey 2011). Legal barriers that prevent charges being varied are also a potential explanation for the absence of state-dependent pricing.

[2] Notably, Zhang et al. (2005) and (2008) analyze how individuals adjust their travel schedules in response to the occurrence of congestion and congestion–mitigation measures, such as road pricing and parking pricing. The results in Zhang et al. (2008) indicate that morning road tolls results in an optimal arrival traffic pattern to

related work is Johansson-Stenman (2006), who developed a theoretical framework to study the optimal road charge when congestion increases road users' fuel and wear-and-tear costs, as well as the emission release by automobile per km. He showed that optimal road charges should take account of all these dimensions: road users should pay not only for the direct time and environmental costs that they impose, but also for the increase in other road users' fuel costs, wear-and-tear costs and exhaust emissions.

His work differs from ours in two important ways. First, unlike his study, in ours, price differentiation is an optimal response to the physical environment; higher fees at a certain time of the day are optimal since they discourage traffic when the assimilate capacity is constrained. By accounting explicitly for the role of the assimilative capacity on optimal road pricing, we allow for a more comprehensive view of the economy-ecology interactions at stake. Second, the feasibility of the policy insights derived from the analysis. Practical road-pricing systems must reflect trade-offs between allocative efficiency and simplicity. While it remains unfeasible to differentiate congestion charges according to the indirect effects caused by road users, most congestion charges in place do resemble variable price schemes to some extent as they incorporate price bans to mitigate congestion.[3] Our analysis indicates that such price variations should also be a response to limited air mixing resulting in reduced assimilative capacity.

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.

the bottleneck and the economic benefits are twofold: it makes parking spots less competitive in the morning commute, and thus reduces the schedule delay cost by shortening the morning rush hour to the minimal value while it also eliminates the queuing delay.

[3] 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.

II. Temporal variation of air pollution and assimilative capacity

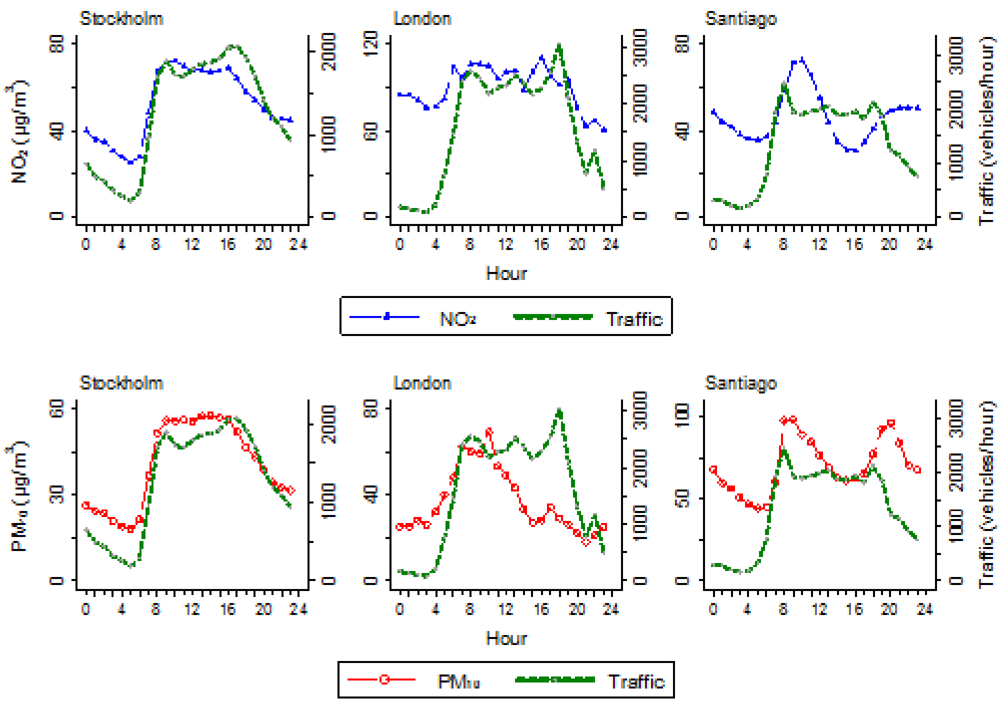
Understanding urban air pollution due to road transportation is complex because several factors affect pollutants' dynamics and air quality. Air pollution levels from road transportation depend on polluters' type and number, meteorology, topography including the arrangement of houses along streets and traffic routes, driving patterns, and sectorial policies in place. Because the levels and particular causes of pollution vary from one city to another, we present a sample of cities around the world to highlight the main patterns of diurnal variation of air pollution. Our choice is based on availability of data and the importance of traffic-related air pollution: it includes heavily polluted as well as cleaner cities. As shown in Figure 1, we display the diurnal patterns of [NO_2] and [PM_{10}], and traffic flows in Stockholm (Sweden), London (United Kingdom), and Santiago (Chile).

Regarding our choice of cities, most of the air pollution in Stockholm comes from heavy vehicles and cars with winter tires that tear heavy particles off the roads. Despite Stockholm has being ranked as one of the cleanest large cities in Europe[4], in 2011 Sweden was sentenced a fine by the European Court since several cities – including Stockholm - fail to comply with AQSs. The fine has not officially determined yet, but it is expected to range between 20 and 90 million SEK (2 to 9 million €). In addition Sweden is expected to pay a daily fine in the range of 200 000 – 500 000 SEK (20 000 – 50 000 €) for each day the AQSs are violated. When it comes to London, the significant contribution of road transport to air pollution is widely acknowledged. Official government figures revealed, for instance, that in 2011 traffic was responsible for approximately 60% of the total emissions of nitrogen oxide (NO_x), PM_{10} and $PM_{2.5}$ within the City of London (CERC 2011). Finally, Santiago is one of the Latin American capitals with the worst air quality, and the transportation sector is estimated to account for over 86% and 75% of PM_{10} and NO_2 emissions, respectively (Bell et al. 2006).

For all cities, we used hourly data on pollutant concentrations from the national Air Quality Networks to describe the average daily profiles of concentrations. In each case, we selected monitoring stations located in central areas that are most affected by vehicular traffic (see Appendix A for further details). To explore the relationship between traffic and pollution, we plotted the flow of vehicles per hour in the traffic monitoring station closest to the pollution monitoring station (Figure 1).

[4] See Aphekom (2011).

Figure 1: Hourly patterns of air pollution in Stockholm, London and Santiago.



Some interesting patterns appear:

Hourly [NO_2] and [PM_{10}] vary significantly during the day, as does traffic flows. In our sampled cities, traffic flows exhibit two clear peaks (one in the morning and one in the afternoon). Whether pollution peaks occur in hours of peak traffic depends on the pollutant under analysis. For example, [NO_2] is clearly related to traffic flows, while [PM_{10}] tends to peak after the first traffic peak has occurred.

Nevertheless, despite [NO_2] being strongly influenced by traffic, it is not perfectly correlated to traffic peaks. For instance, [NO_2] responds quickly to changes in the vehicle fleet in the morning (i.e. the concentration peak is reached within one hour after the traffic peak) while it responds more slowly and to a smaller extent in the afternoon. Interestingly, the traffic peak in the afternoon (in most cases larger than the morning traffic peak) is associated with a much lower level of [NO_2]. The ratio [NO_2] morning/afternoon is approximately 1.5 in Santiago, 1.12 in London and 1.25 in Stockholm.[5]

[5] Similar evidence is found by Holzworth (1967) for Los Angeles (United States), by Wang and Xie (2009) for Beijing (China), by Arain et al. (2007) for Toronto (Canada), and by Kim et al. (2012) for Seoul. Higher relative

The correlation between traffic flows and [PM_{10}] is less clear than in the case of [NO_2]. This might be explained by the fact that a fraction of PM_{10} emissions comes from other sources, e.g. road dust, construction work, pollen material, spores and sea spray. These sources are subject to seasonal variation. Suspended pollen material contributes mainly during the growing season. Particles originating from road dust increase during dry conditions and high wind speeds. In Sweden, this is especially important during spring, when roads dry up and big deposits of grit from the winter remain on the roads (Johansson et al. 2007). Moreover, [PM_{10}] might be affected by meteorological conditions that do not exhibit a clear pattern during the day, such as precipitation that reduces airborne particles and flushes away PM_{10} emissions. Nevertheless, from the figures, we can still observe that, for the cities included, [PM_{10}] closely follows the pattern of traffic when the traffic is building to the peak. In addition, morning traffic peaks coincide with peaks of [PM_{10}], but the afternoon traffic peak shows a comparatively lower level of [PM_{10}]. This could be explained by the diurnal wind pattern. Higher wind speeds in the afternoon tend to disperse the emitted particles better, resulting in a lower [PM_{10}]. Alternatively, the contribution of non-traffic related sources is larger during off-peak traffic hours, which would explain for, example, the high [PM_{10}] in Stockholm at midday when traffic is at a dip.

The imperfect correlation between pollution concentrations and traffic flows observed for our cities is consistent with scientific literature reporting that the effect of road transportation emissions on concentrations is critically affected by changes in the assimilative capacity, which is heavily influenced by meteorological conditions (Holst et al. 2008, Rost et al. 2009 and Jones et al. 2010). For instance, anticyclonic weather and temperature inversions near the ground favor high pollutant concentrations. During these conditions, a stagnant layer of air traps air pollutants near the ground, impeding pollutant dispersion (Grunström et al. 2011).

What are the implications of the strong variation in dispersion/assimilative capacity for optimal road pricing? The optimal management of a pollutant requires policies that restrict emissions when they cause the most damage, while inducing behavioral adjustments leading to relatively higher emissions when the assimilative capacity of the environment is larger. In the following section, we illustrate the dynamics of a congestion charge consistent with the variation in assimilative capacity in the case of Stockholm, Sweden. We focus on [NO_2] and [PM_{10}] with current AQSs at 90 $\mu g/m^3$ per hour and 50 $\mu g/m^3$ per day, respectively. The [NO_2] standard should not be violated more than 175 times per year (2% of the time). In the case of [PM_{10}], the standard can be exceeded no more than 35 times per year (10% of the time). Despite the implementation of the congestion charge, NO_2 and PM_{10} are the urban

---

concentrations of pollutants occur in the morning than in the afternoon, reflecting the diurnal variations of mixing depths and wind speeds.

air pollutants for which concentrations allowed under AQSs are regularly exceeded along densely trafficked streets of Stockholm (Johansson et al. 2009).

III. Differentiated Road Pricing: An Application to the Case of Stockholm

Our methodology is based on the following steps. Firstly, using data for Stockholm during the period 2002-2010, we estimate the empirical relationship between [NO_2], [PM_{10}], traffic flows and assimilative capacity per hour and season. In line with previous studies, we use wind speed as a proxy of assimilative capacity (Goya et al. 2006, Goyal and Chalapi Rao 2007 and Jones et al. 2010). Secondly, we use the estimates above to forecast the traffic flow per hour (and season) consistent with compliance of the Swedish AQSs for [NO_2] and [PM_{10}]. Finally, we estimate the price elasticity of the traffic flow across the Stockholm's cordon with respect to the congestion charge to calculate the variation in the charge needed to bring the actual level of traffic flow to the level of traffic flow needed to comply with the AQSs calculated in the second step. Thus, we used predicted and observed traffic flows in the cordon, and the elasticity of traffic to the congestion charge as inputs to obtain the time-varying congestion charge consistent with the AQSs.

From a theoretical point of view, it would be optimal to implement a time-varying congestion charge that takes account not only of variation of the assimilative capacity throughout the day but also across days. However, from a practical point of view, the main purpose of the congestion charge is to ensure that in deciding when or whether to travel or by which route, travellers take account of the costs that their travel choice will impose on others. If the congestion charge is to fulfill this price signaling function, it is essential that it is known accurately by each traveller before they make their travel choices. For this reason, and to keep the administrative costs low, it may be desirable to maintain the daily time-varying pattern for a certain part of the year.

We chose to develop our estimations per season because it allows us to characterize major variations in the assimilative capacity due to seasonal variation in meteorological conditions, while maintaining the potential for policy implementation of our results.

This section is organized as follows. Firstly, we briefly describe the main features of the congestion charge in place and its effect on reducing congestion and pollution to date. Secondly, we present the model employed to characterize the dynamics of assimilative capacity during the day and its effects on pollution concentration. Thirdly, we compute our estimates of the time-varying charge that account for variations in the assimilative capacity.

3.1 Stockholm's Congestion *Charge*

The congestion charge in Stockholm is a cordon toll system that surrounds the entire city center, with a total area of approximately 35.5 km^2. It was implemented on 1 August 2007 with the purpose of reducing both traffic congestion and emissions. It is incurred both at entry into and exit from any of the 18 entry and exit points between 6.30 and 18.30. It has three price bands, depending on time of the day, which makes it a variable price scheme. The charge is higher when congestion is expected to build up to a peak and lower at other times of the day. Thus, the cost of passing the cordon on week days is SEK 20 (approx. € 2) during peak hours (7:30–8:30, 16:00–17:30), SEK 15 (approx. € 1.5) during the shoulders of the peaks (30 minutes before and after peak periods: 7:00-7:30, 8:30-9:00, 15:30-16:00 and 17:30-18:00) and SEK 10 (approx. € 1) during the rest of the period (6:30-7:00 and 9:00-15:30). The charge is levied in both directions, and the maximum total charge per day is SEK 60 (approx. € 6). There is no charge in the evening or at night; on Saturdays, Sundays, public holidays or the day before such a holiday; or during the month of July.

Vehicles are registered and identified automatically by taking a photograph of their number plate, which is analyzed using Optical Character Recognition technology. Payment is made monthly after an invoice is sent to the registered owner of the vehicle.

The charge has been in place for more than five years, and measurement of the effects has been extensive (Börjesson et al. 2012, Eliasson 2008 and 2009, Eliasson et al. 2009, Karlström and Franklin 2009 and Kristofferson 2013). Studies have shown that traffic over the taxed cordon was reduced significantly after the permanent implementation of the charge (approximately 18.75% over the period 2008-2011). The congestion charge also proved to have a significant effect in reducing journey times: queuing times were reduced to half during morning peak in the inner road system subject to taxation, whereas there was no increase over the 2007 and 2008 traffic levels in the inner city, suggesting that there was no tendency to increase use of road space free from congestion charge. Moreover, emissions from traffic were also reduced (the estimated reductions of air-borne pollutants inside the cordon varied from 10% to 14%). The number of traffic accidents was reduced as well, contributing to an increase in traffic safety, both in terms of fatal accidents and severe injury accidents. [6]

---

[6] There is some evidence of the morning peak of traffic spreading toward a later departure time due to the charge (Kalström and Franklin 2009). Changes in departure time are important in the context of equity and redistribution, as the poor may be less flexible in departure time than the rich. This aspect is, however, beyond the scope of our study.

3.2 *The Dynamics of the Assimilative Capacity*

Using information on hourly pollutant concentrations, wind speed and traffic flow obtained from the SLB-analysis unit of Stockholm City's Environment and Health Administration[7], we estimate separately the relationship between assimilative capacity per season and [NO_2] and [PM_{10}] as:

(6) $$C_t = k_1 + \frac{k_2 F_t}{A_t^{k_{3t}}}.$$

Where C_t, represents [NO_2] or [PM_{10}]; F_t and A_t are traffic flow and wind speed, respectively, at time t; k_1 and k_2 are two time-invariant constants; and k_3 is a time-variant (by hour of the day) constant that accounts for the role of wind speed dispersing pollution at different rates throughout the day. k_1 represents the background concentration, which is not affected by local traffic. k_2 is a proportionality constant which assumes a linear relationship between traffic flow and the contribution to air pollution concentration by local traffic. A_t^{k3t} represents the assimilative capacity. It can be shown that urban air pollution concentration above a background level (represented by k_1) is strongly and negatively related to wind speed (Rost et al. 2009 and Jones et al. 2010) and that the relationship is strongly non-linear. Rising wind speed (A_t) to the power of k_{3t} allows for this non-linearity. Moreover, the probability that concentrations will exceed the AQSs depends strongly on both traffic flows and wind speed. As seen in Figure 2, for the highest wind speed interval (i.e., wind speed larger than 8 m/s), the probability of exceeding the concentration allowed under the AQS for [NO_2] is almost zero, even for large traffic flows. For [PM_{10}], the relationship is less clear, since, at low wind speeds, the small combustion particles are likely to be predominant, while the fraction of dust particles will increase at higher wind speeds.

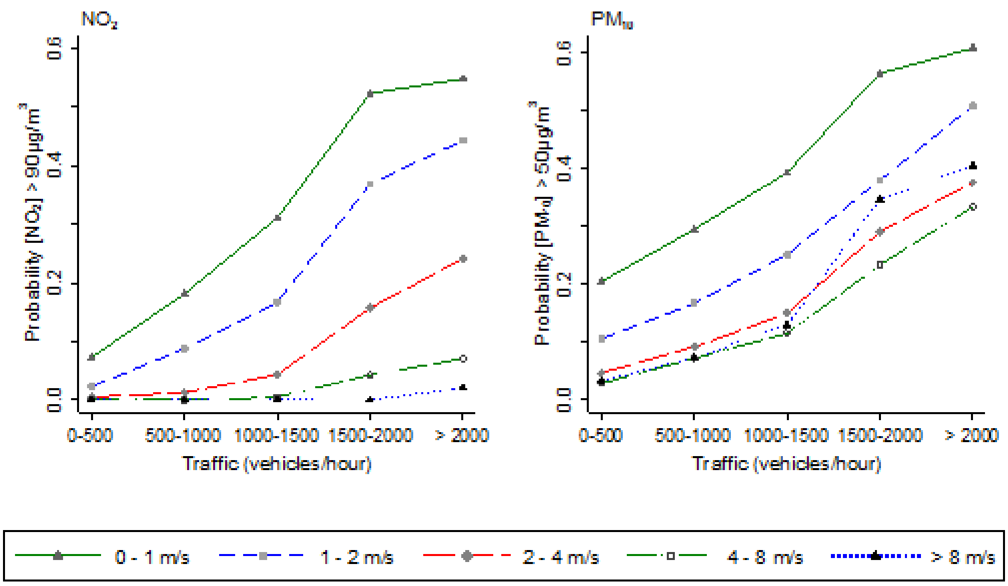
[PM_{10}] is also sensitive to precipitation, which the model does not take into consideration (Holst et al. 2008 and Rost et al. 2009).[8] Nevertheless, a statistical analysis of the daily profile of precipitation in Stockholm indicates a random pattern over the day within each season, with most of the variation

[7] [NO2] and [PM10] are obtained from the monitoring site Hornsgatan located at ground level on the south side of the street in a typical inner city environment that is highly influenced by traffic, with approximately 30 000 vehicles per workday. Wind speed measurements are collected at the monitoring station Torkel Knutssonsgatan, located around 100 m south of the street Hornsgatan. Traffic counts correspond to the total traffic for four lanes, and are measured on Hornsgatan adjacent to the Hornsgatan air quality station between the streets Ringvägen and Anskariegatan.

[8] Precipitation and mixing layer height seem to be the meteorological variables influencing near-surface [PM_{10}] most significantly within cities (Rost et al. 2009 and Jones et al. 2010); the absence of precipitation and low values of the mixing layer height lead to comparatively high PM_{10} levels. Because wind speed normally varies with height, in this study we use the average wind speed through the mixing depth as a convenient representation of the horizontal transport of air within the mixing layer.

occurring across seasons. Thus, though precipitation might affect the level of pollution concentration (which is captured through k_1), it does not explain its variation throughout the day.

Figure 2: Traffic Flows, Wind Speed and Probability of Exceeding AQS for [NO_2] and [PM_{10}] AQSs



We estimate equation (6) using Nonlinear Least Squares (NLS) for each pollutant and season of the year during workdays.[9] Our estimates for [NO_2] and [PM_{10}] (including heteroscedasticity and autocorrelation consistent Newey-West standard errors for 24 lags of the diurnal profile for concentrations) are reported in Appendix A. As expected, the coefficient for background concentration k_1 and traffic volume k_2 are positive and statistically significant for both pollutants. Moreover, for both pollutants, several of the time-variant coefficients associated with wind speed are statistically significant, which happens at times when the highest concentrations or concentrations exceeding permissible levels occur. The variation in size of these coefficients also supports the presence of different effects of wind dispersing pollutants throughout the day.

[9] Nonlinear Least Squares consists of minimizing the sum of squared residuals of the nonlinear regression. The estimates are computed by numerical methods. This approach has been widely used in transport economics (see Bolduc et al. 2013, Moghadam and Livernois 2010, and Chou 1993 for some applications).

The overall performance of the model was alsstatistically evaluated using the Likelihood Ratio Test (LR). We also performed LR tests of the null hypothesis that k_3 is a time-invariant coefficient versus the alternative hypothesis that k_3 varies over time as in specification (6). The tests reject the hypothesis of no temporal variation in the influence of wind speed on assimilative capacity during the day, at the 1% significance level. We plot the observed and predicted hourly means of [NO_2] and [PM_{10}] along the traffic flows and wind speed for each season in Figure 3 and 4. As can be seen from the figures, the highest [NO_2] and [PM_{10}] are observed during spring, and the lowest [NO_2] and [PM_{10}] are observed during summer/autumn; daily average [NO_2] and [PM_{10}] are respectively circa 60 $\mu g/m^3$ and 70 $\mu g/m^3$ in spring and 50 $\mu g/m^3$ and 30 $\mu g/m^3$ in summer and autumn. Furthermore, we can see that despite its simplicity, our model succeeds in replicating the level and rate of variation of pollution concentration throughout the day in Stockholm indicating that the model satisfactorily captures and reproduces the diurnal pattern of concentrations.

Figure 3: Diurnal profile of observed and fitted [NO_2], traffic flows and wind speed by season

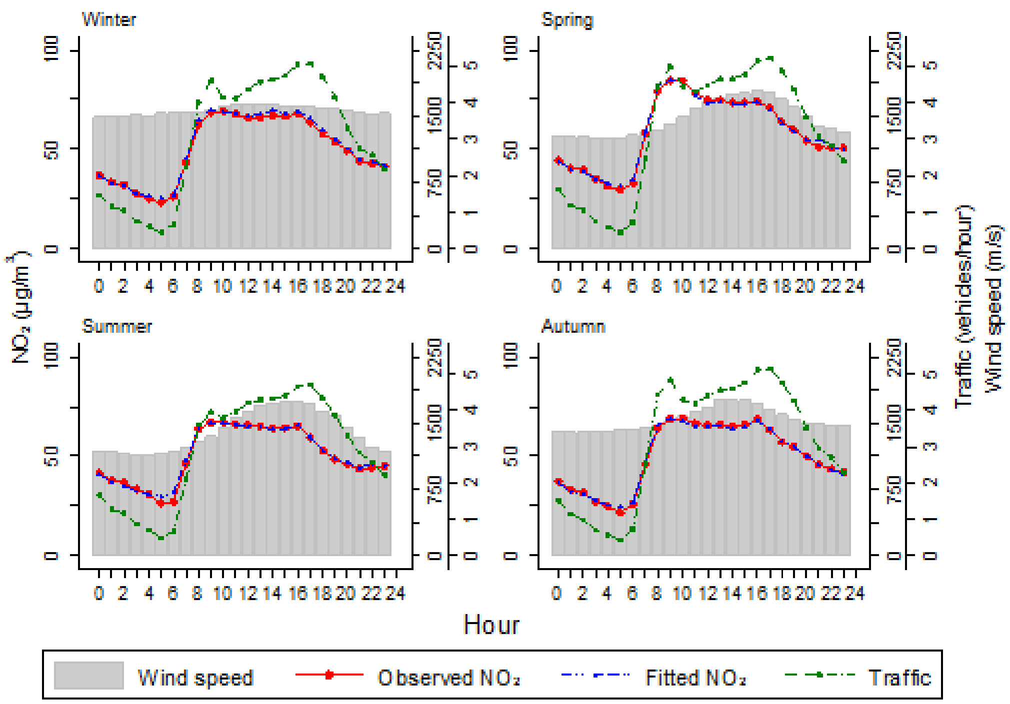
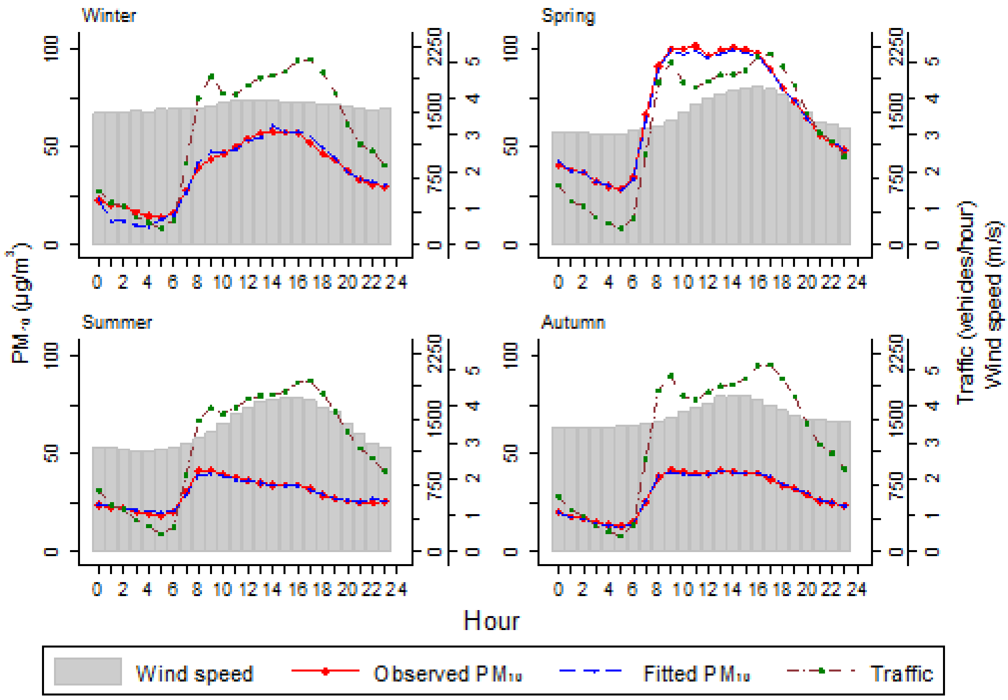


Figure 4: Diurnal profile of observed and fitted [PM_{10}], traffic flows and wind speed by season



3.3 Assimilative Capacity and Time-Varying Charges in Stockholm

By using equation (6), we solve for the traffic flows consistent with the air quality standards of [NO_2] and [PM_{10}] as follows[10]:

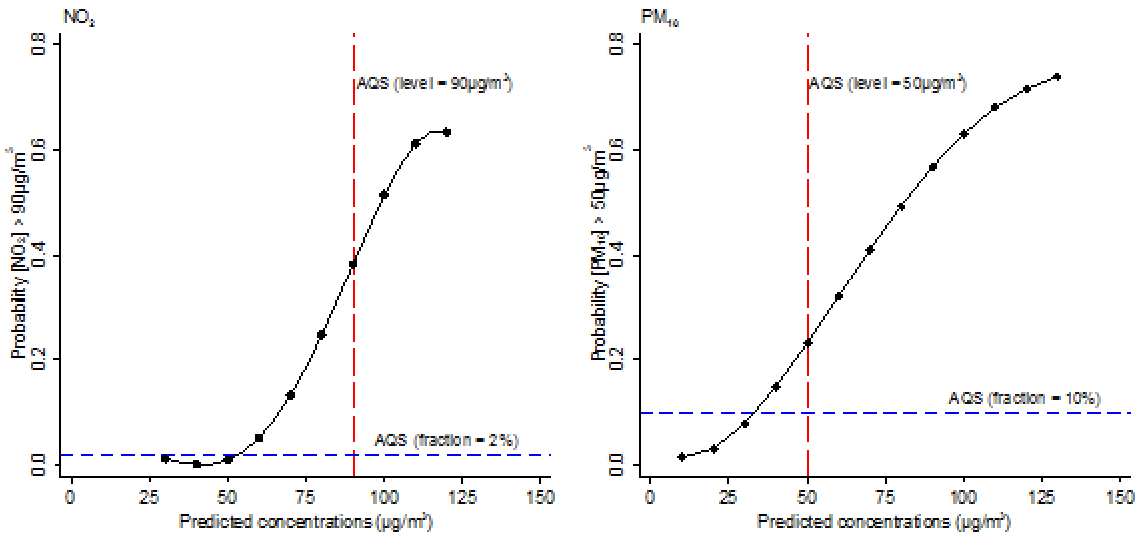
(7) $$F_t = \frac{A_t^{k_3 t}\left[C_t^{AQS} - k_1\right]}{k_2}.$$

Note that in order to forecast the traffic flow, we need to feed our formula with the parameters estimated in the previous section, and the mean values of wind speed for each hour of the day per season. Because the prediction is based on the mean hourly value of wind speed, this method does not take account of the variability of wind speed and its effects on pollution concentration. To ensure that the traffic flows are consistent with concentrations that do not exceed permissible levels under AQSs, we estimate the empirical relationship between the pollutants' concentrations predicted by

[10] Note that our analysis is performed on an hourly basis. In the case of [NO_2], this is consistent with the time frame of the AQS, which is defined as a maximum concentration per hour. In the case of [PM_{10}], however, the standard is defined as a 24 hour average. There are many profiles of concentrations per hour consistent with such a standard. To keep the analysis simple, we only focus on the case where the hourly concentration of PM_{10} does not violate the standard at any hour of the day. This precautionary approach is nevertheless consistent with evidence from toxicological and clinical studies showing that peak exposures of short duration to PM_{10} (ranging from less than an hour up to a few hours) lead to immediate physiological changes.

our model and the actual fraction of hours with [NO_2] larger than 90 μg/m^3 and [PM_{10}] larger than 50 μg/m^3. These empirical distributions are presented in Figure 5. They indicate that to ensure that [NO_2] and [PM_{10}] AQSs are exceeded no more than 2% and 10% of the time, respectively, one has to target a much lower average hourly concentration than the concentration imposed by the AQSs. Notably, the mean [NO_2] and [PM_{10}] should be equal to 55 μg/m^3 and 35 μg/m^3 to avoid exceeding of AQSs (Figure 5). This is to say that in our estimates C_t^{AQS} takes a value equal to 55 μg/m^3 and 35 μg/m^3 for [NO_2] and [PM_{10}] respectively.

Figure 5: Empirical Distribution of Exceeding AQS and Predicted [NO_2] and [PM_{10}][11]



Our next step is to calculate the difference between the actual traffic flow (F_t) and traffic flow per hour consistent with the AQS (F_t^{AQS}) by using historical records and the estimates computed through equation (7). For each pollutant, this difference is defined as $\Delta F_t = \frac{F_t - F_t^{AQS}}{F_t}$.

For those hours where $\Delta F_t > 0$, the actual traffic flow should be reduced through an increased congestion charge, while the reverse holds when $\Delta F_t < 0$. To what extent should the charge be increased or reduced? In order to provide an answer to this question, we estimate the price elasticity

[11] The graphs of the empirical distribution of the probability of exceeding AQS and the predicted [NO_2] and [PM_{10}] were fitted with a polynomial of order four. The empirical and the fitted distribution showed a high goodness of fit (R^2 = 0.99).

of traffic flows to the congestion charge η_t. In calculating the elasticity, we follow the methodology by Börjesson et al. (2012), who compute the elasticity in response to the congestion charge as $\eta_i = \frac{\ln(F^i_{2010}/F^i_{2005})}{\ln(P^i_{2010}/P^i_{2005})}$, where $(F^i_{2010,}P^i_{2010})$ and (F^i_{2005}, P^i_{2005}) are the traffic flows of non-exempt traffic[12] and total travel costs in real terms in years 2010 and 2005 respectively. We estimate η_t for three time windows: morning (06:30-09:00), off-peak period (09:00-15:30) and afternoon (15:30-18:30) to take account of the fact that the responsiveness to the charge might vary throughout the day. Following Börjesson et al. (2012), we assume that the mean length of trips crossing the cordon was 13 km, as indicated by surveys carried out before and after the implementation of the congestion charge. The average total trip costs in real terms for 2010 corresponded to 32.3, 27.5 and 32.8 SEK, respectively, in contrast to a value of 19.5 SEK in 2005. The overall average traffic reductions of non-exempt traffic during the morning, off-peak and afternoon between the years 2010 and 2005 were equivalent to 25.2%, 32.5% and 37.2%, respectively. This yields elasticity estimates of -0.58, -1.14 and -0.89, respectively.

By using these estimates, for each pollutant we compute the difference between the actual congestion charge (P_t) and the congestion charge representing no concentrations exceeding permissible levels (P_t^{AQS}) as $\Delta P_t = \Delta F_t/\eta_t$, where $\Delta P_t = \frac{\left[P_t - P_t^{AQS}\right]}{P_t}$.

Finally, note that the daily profiles for [NO_2] and [PM_{10}] differ considerably, leading to a very different time varying congestion charge. To account for this, we take a precautionary approach and compute the (final) charge as the value needed to comply with both AQSs, i.e. $P_t^{AQS} = max\left[P_t^{AQS_{NO_2}}, P_t^{AQS_{PM_{10}}}\right]$. The results are presented in Figure 6.

[12] In 2007, the charge became tax deductible for those commuters travelling more than 5 km and who could save at least one hour compared to public transportation one way; this applied to approximately 8% of all car trips across the cordon. They were granted a 60% charge reduction. Moreover, ''company cars'' (i.e., company-owned cars used by an employee for both work-related and private purposes), which account for 23% of all vehicles crossing the charging cordon, receive at least a 60% reduction of the congestion charge, and about 20% of all company cars pay no charge at all.

Figure 6: Actual vs. Time-Varying Charge Consistent with AQS per Season

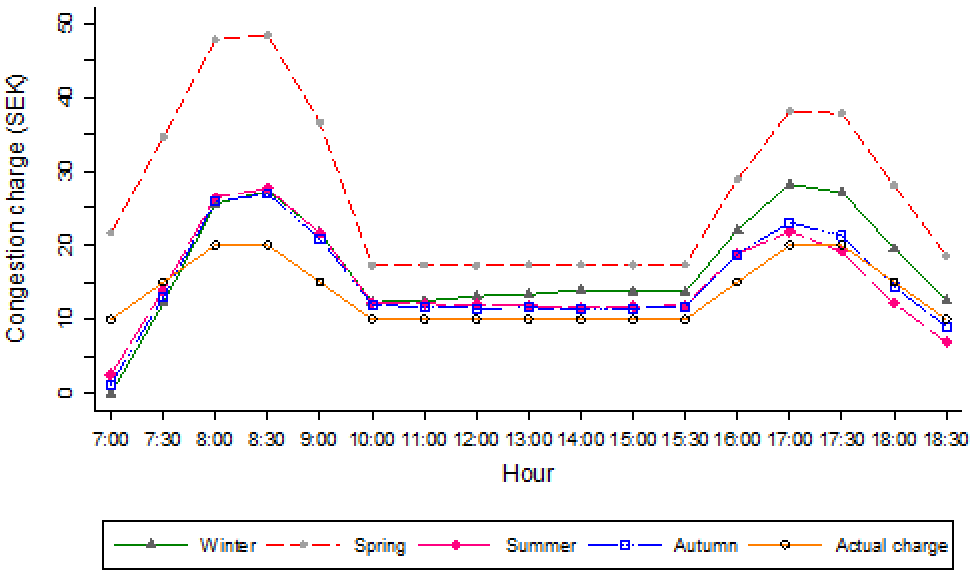


Figure 6 displays the combined effect of different traffic flows per hour and season, hourly and seasonal dynamics of [NO_2] and [PM_{10}], and different price elasticities per time of the day. It indicates that, with regard to the current time-varying schedule, the achievement of AQSs in Stockholm would require the charge to be increased for all seasons and most hours of the day. In relative terms, a much larger increase is needed in spring. The increment should be also larger in the morning to offset the negative effect of reduced assimilative capacity on pollution concentration; in the case of spring, the charge should more than double during morning peak hours. The increment in the charge should be smaller for the remaining seasons due to increased pollution dispersion resulting from more favorable meteorological conditions and, in the case of summer, much reduced traffic flows.

The seasonal dynamics of [PM_{10}] is the main driver behind the need for an increased charge in spring, while [NO_2] explains the need for an increased charge for the remaining seasons. The need for a larger time-varying congestion charge in spring coincides with an increased contribution of PM_{10} emissions by other sources, such as suspended road dust and pollen fragments. Our results indicate that, in order to achieve the same AQS for [PM_{10}], a much larger contribution to reductions from road transportation is required to compensate for the increased emissions coming from other sources.

Our temporally differentiated congestion charge would ensure that [NO_2] and [PM_{10}] AQSs would not be violated more than 2% and 10% of the time, respectively; but it would also result in sizeable reductions of [NO_2] and [PM_{10}] for all seasons. [NO_2] and [PM_{10}] are estimated to be reduced by 31.4% and 42.4% (respectively) during spring, 7.3% and 7% during summer, 8.8% and 10.7% during autumn, and 13% and 19.8% during winter. The willingness to pay (WTP) for improved air quality in Sweden has been estimated by Carlsson and Johansson-Stenman (2000). Their results indicate that the mean WTP for a 50% reduction of harmful substances where the respondents live and work is about € 240 per person per year[13], which is of the same order of magnitude as earlier stated preference studies in Nordic countries. Using their estimates and under the strong assumption of a linear damage WTP function in concentration levels, we can compute the value of the pollution reduction due to the varying-fee to be equal to approx. €84.5 per person per year. Given a population of 881 235 inhabitants in the city of Stockholm, this would imply an aggregate WTP of about € 74.5 million per year. On the other hand, the increased charge would also lead to a reduction of revenues of about € 33 276 per year (See Table 1). Thus, the time varying congestion charge would generate significant benefits due to improved air quality and avoidance of EU fines at expenses of a (relatively) minor reduction of congestion charge's revenues. Clearly, the implementation of such a fee would also generate a series of other positive side effects as the reduction of congestion, travel times and traffic accidents though at expense of a reduction of drivers' consumer surplus due to increased travel costs due to the charge.

Table 1: Reduction of pollution and traffic flows per season.

Season	NO_2 Reduction (%)	PM_{10} Reduction (%)	Average NO_2-PM_{10} Reduction (%)	WTP per Season (€ /person)	Average Reduction in Traffic Flows (%)	Reduction in Revenues (€)
Spring	31.4	42.4	36.9	44.44	80.6	26979
Summer	7.3	7,0	7.15	8.61	9.2	1242
Autumn	8.8	10.7	9.75	11.74	9.4	1019
Winter	13	19.8	16.4	19.75	24.3	4036
Year	15.13	20.0	17.6	84.5	30.88	33276

[13] € 200 in terms of 1996's monetary values.

IV. Conclusions

Considering the urgency of improving air quality in many countries around the world, it is important to use environmental policy instruments that restrict emissions when they cause the most damage. In this paper, we suggest a congestion charge that takes account of the economy-ecology interactions at stake in Stockholm, Sweden. A distinguishing feature of our analysis is that the time-varying charge depends on the rate at which pollution is dispersed. Our results indicate that, in order to achieve the AQSs, the congestion charge should be increased for all seasons and most hours of the day. Moreover, there is important variation in the level of the time-varying charge per season; the level should be larger in spring due to less favorable meteorological conditions for pollution dispersion and increased contribution from pollution sources other than vehicle exhaust. Regarding the daily profile, during most seasons a larger charge is also needed in the mornings to offset the negative effects of the limited assimilative capacity. The charge would not only ensure compliance with AQSs, but it would also result in sizeable reductions of [NO_2] and [PM_{10}] for all seasons.

In our analysis, we have modeled the dynamics of the relationship between pollution concentration and traffic flows in the specific case of Stockholm in a simplified way. For instance, we disregard spatial considerations and investigate the cordon-based congestion pricing problem consistent with the compliance of AQSs in a mono-centric city. In addition, our time varying is not designed to maximize social welfare but to ensure compliance with AQSs. Further research would be needed to explore these issues. Nevertheless, this study provides a useful starting point for assessing the role of the assimilative capacity on optimal road pricing. Moreover, the basic principles and the methodology developed in this paper could be easily adapted to other cities. In some cases, this might require inclusion of further meteorological variables in the analysis, for example precipitation in the case of [PM_{10}] where wind speed has a strong diurnal or seasonal pattern. Even if this might impose additional challenges, such information is available for most countries.

V. References

Anas A and Lindsey R. 2011. Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice. Review of Environmental Economic Policy 5 (1): 66-88.

Aphekom. 2011. Summary report of the Aphekom project 2008-2011. Improving Knowledge and Communication for Decision Making on Air Pollution and Health in Europe. Report downloadable from: www.aphekom.org/c/document_library/get_file?uuid=5532fafa-921f-4ab1-9ed9-c0148f7da36a&groupId=10347

Arain M-A, Blair R, Finkelstein N, Brook J-R, Sahsuvaroglu T, Beckerman B, Zhang L, and Jerrett M. 2007. The use of wind fields in a land use regression model to predict air pollution concentrations for health exposure studies. *Atmospheric Environment* 41(16): 3453–3464.

Bell M-L, Davis D-L, Gouveia N, Borja Aburto V-H, and Cifuentes L. 2006. The avoidable health effects of air pollution in three Latin American cities Santiago Sao Paulo and Mexico City. *Environmental Research* 1: 431-44.

Bolduc D, Bonin S and Lee-Gosselin M. 2013. A disaggregated tool for evaluation of road safety policies. Research in Transportation Economics 37: 79-98.

Börjesson M, Eliasson J, Hugosson M-B, and Brundell-Freij K. 2012. The Stockholm congestion charges—5 years on. Effects, acceptability and lessons learnt. *Transport Policy* 20(1): 1-12.

Carlsson F and Johansson-Stenman O. 2000. Willingness to pay for improved air quality in Sweden. Applied Economics 32: 661-669.

CERC (Cambridge Environmental Research Consultants). 2011. Source Apportionment for the City of London Corporation. Report available at: http://www.cityoflondon.gov.uk/business/environmental-health/environmental-protection/air-quality/air qualityreports/Documents/source%20apportionment%2015Jun11.pdf

Cheng L and Yang H. 2012. Managing congestion and emissions in road networks with tolls and rebates. Transportation Research Part B 46: 933–948.

Chou Y.H. 1993. A method for measuring the spatial concentration of airline travel demand. Transportation Research Part B 27 (4): 267-273.

Eliasson J. 2009. A cost-benefit analysis of the Stockholm congestion charging system. Transportation Research Part A: Policy and Practice 43 (4): 468-480.

Eliasson J. 2008. Lessons from the Stockholm Congestion Trial. *Transport Policy* 15(6): 395-404.

Eliasson J, Hultkrantz L, Nerhagen L, and Smidfelt Rosqvist L. 2009. The Stockholm congestion - charging trial 2006: Overview of effects. Transportation Research Part A: Policy and Practice 43(3): 240-250.

Goyal P, Anand S, and Gera B.S. 2006. Assimilative capacity and pollutant dispersion studies for Gangtok city. *Atmospheric Environment* 40: 1671-1682.

Goyal P and Chalapi Rao C-V. 2007. Assessment of atmospheric assimilation potential for industrial development in an urban environment: Kochi (India). *Science of the Total Environment* 376: 27–39.

Grundström M, Linderholm H-W, Klingberg J, and Pleijel H. 2011. Urban NO2 and NO pollution in relation to the North Atlantic Oscillation NAO. *Atmospheric Environment* 45(4): 883-888.

Hayas A, Gonzalez C-F., Pardo G, and Martinez M-C. 1981. Diurnal variation of particulate pollution of the atmosphere in an urban area. *Atmospheric Environment* 15(3): 411–413.

Holst J, Mayer H, and Holst T. 2008. Effect of meteorological exchange conditions on PM10 concentration. *Meteorologische Zeitschrift* 17(3): 273-282.

Holzworth G-C. 1967. Mixing Depths, Wind Speeds and Air Pollution Potential for Selected Locations in United States. *Journal of Applied Meteorology* 6: 1039-1044.

International Institute for Applied Systems Analysis IIASA. 2012. TSAP-2012 Baseline: Health and Environmental Impacts. Report available at: http://www.iiasa.ac.at/web/home/research/researchPrograms/MitigationofAirPollutionandGreenhousegases/TSAP- IMPACTS-20121126.pdf

Johansson C, Burman L, and Forsberg B. 2009. The effects of congestions tax on air quality and health. *Atmospheric Environment* 4: 4843-4854.

Johansson C, Norman M, and Gidhagen L. 2007. Spatial & temporal variations of PM_{10} and particle number concentrations in urban air. *Environmental Monitoring and Assessment* 127(1-3): 477-487.

Johansson-Stenman O. 2006. Optimal environmental road pricing. *Economic Letters* 90(2):225-229.

Joksimovic D, Bliemer M-C, and Bovy P-H-L. 2005. Optimal toll design problems in dynamic traffic networks with joint route and departure time choice. Transportation Research Record 1923, 61-72.

Jones A-M, Harrison R-M, and Baker J. 2010. The wind speed dependence of the concentrations of airborne particulate matter and NO_x. *Atmospheric Environment* 44: 1682-1690.

Karlström A and Franklin J-P. 2009. Behavioral adjustments and equity effects of congestion pricing: Analysis of morning commutes during the Stockholm Trial. Transportation Research Part A 43: 283-296.

Kim W, Lee H, Kim J, Jeong U, and Kweon J. 2012. Estimation of seasonal diurnal variations in primary and secondary organic carbon concentrations in the urban atmosphere: EC tracer and multiple regression approaches. *Atmospheric Environment* 56: 101–108.

Kristofferson I. 2013. Impacts of time-varying cordon pricing: Validation and application of mesoscopic model for Stockholm. Transport Policy 28: 51–60.

Levinson D-M and Odlyzko A. 2008. Too expensive to meter: the influence of transaction costs in transportation and communication. Philosophical Transactions of the Royal Society A 366 (1872), 2033–2046.

Lindsey R. 2011. State-dependent congestion pricing with reference-dependent preferences. Transportation Research Part B 45: 1501–1526

Mikhailuta S-V, Taseiko O-V, Pitt A, Lezhenin A-A, and Zakharov Y-V. 2009. Seasonal variations of air pollutant concentrations within Krasnoyarsk City. *Environ Monitoring Assessment* 149(1-4): 329-341.

Moghadam A-K. and Livernois J. 2010. The abatement cost function for a representative vehicle inspection and maintenance program. Transportation Research Part D 15: 285–297.

Rost J, Holst T, Sähn E, Klingner M, Anke K, Ahrens D, and Mayer H. 2009. Variability of PM10 concentrations dependent on meteorological conditions. *International Journal of Environment & Pollution* 36(1-3): 3 – 18.

Small K-A, Yan J. 2001. The Value of “Value Pricing” of Roads: Second-Best Pricing and Product Differentiation. Journal of Urban Economics 49(2): 310-336.

Toth I, Hercog P, Peternel R, and Vojniković B. 2011. Seasonal, daily and intradiurnal variation of PM10, NO2, NO and O3 in residential part of Zagreb, Croatia. Collegium antropologicum 35(2):25-30.

Verhoef E. 2000. The implementation of marginal external cost pricing in road transport. Long run vs. short run and first-best vs. second-best. Papers in Regional Sciences 79(3): 307-332.

Viana M, Pérez C, Querol X, Alastuey A, Nickovic S, and Baldasano J-M. 2005. Spatial and temporal variability of PM levels and composition in a complex summer atmospheric scenario in Barcelona (NE Spain). *Atmospheric Environment* 39: 5343–5361

Wang T and Xie S. 2009. Assessment of traffic-related air pollution in the urban streets before and during the 2008 Beijing Olympic Games traffic control period. *Atmospheric Environment* 43(35):5682-5690.

Wie B and Tobin R-L. 1998. Dynamic Congestion Pricing Models for General Traffic Networks. Transportation Record B 32(5): 313-327.

World Health Organization - European Centre for Environment and Health. 2013. Review of evidence on health aspects of air pollution – REVIHAAP". Report available at:
http://www.euro.who.int/__data/assets/pdf_file/0020/182432/e96762-final.pdf

World Health Organization - European Centre for Environment and Health. 2005. Health effects of transport-related air pollution. Report available at:
http://www.euro.who.int/__data/assets/pdf_file/0006/74715/E86650.pdf

Yildirim M-B and Hearn D-W. 2005. A first best toll pricing framework for variable demand traffic assignment problems. Transportation Research Part B 39: 659–678.

Zhang X, Huang H-J and Zhang H-M. 2008. Integrated daily commuting patterns and optimal road tolls and parking fees in a linear city. Transportation Research Part B 42: 38–56.

Zhang X, Yang H, Huang H-J and Zhang H-M. 2005. Integrated scheduling of daily work activities and morning–evening commutes with bottleneck congestion. Transportation Research Part A 39: 41–60.

Appendix A

Table 1. Description of collected traffic and air quality information

City	Traffic data			Air quality station	Information	Source
	Count points	Location	District			
London	A3211: 75401	Arthur St - Fish St Hill	City of London	Top of Form Upper Thames Street and Walbrook Wharf	October 6th and 16th, 2009. Traffic at 0-6h and 19-23h is projected using the traffic growth rate of M25 road	DfT and LAQN
	A3211: 75400	Queen St Place - Arthur St	City of London			
Santiago	Alameda: E036O0	Jose Victorino Lastarria street-Portugal street	Santiago	Parque O'Higgins	January 2010-December 2010	UOCT and SINCA
	Cardenal Jose Maria Caro: E073O0	Jose Miguel De La Barra street - Purisima Street	Santiago			
Stockholm	Hornsgatan	Ringvägen - Anskariegatan	Central	Hornsgatan	Setpember 2002- December 2010	SLB

Table 2: [NO_2] by season

	[NO_2] Winter	[NO_2] Spring	[NO_2] Summer	[NO_2] Autumn
k1	23.5275***	29.6248***	25.7822***	22.8315***
	(1.2588)	(1.4809)	(1.6034)	(1.1994)
k2	0.0472***	0.0459***	0.0415***	0.0382***
	(0.0021)	(0.0020)	(0.0018)	(0.0015)
g0	0.6592***	0.8198***	0.7115***	0.5549***
	(0.0732)	(0.0784)	(0.0948)	(0.0628)
g1	0.1317	0.0506	0.0891	0.0757
	(0.1001)	(0.1459)	(0.0848)	(0.0674)
g2	0.1768	0.0256	0.1951*	0.1038
	(0.1370)	(0.0961)	(0.1169)	(0.0897)
g3	0.5736	0.2796*	0.3747**	0.3295**
	(0.3547)	(0.1678)	(0.1533)	(0.1351)
g4	0.7179	0.6461	0.4520*	0.9251**
	(0.5628)	(0.5180)	(0.2699)	(0.4489)
g5	0.9547***	0.8653**	0.4309*	0.9409***
	(0.2568)	(0.4116)	(0.2560)	(0.1936)
g6	0.7060**	0.3330**	0.1776	0.7441***
	(0.2841)	(0.1450)	(0.1764)	(0.2204)
g7	-0.0645	-0.3443***	-0.1898**	-0.0586
	(0.0549)	(0.0704)	(0.0785)	(0.0535)
g8	-0.1048*	-0.3387***	-0.2372***	-0.0921
	(0.0618)	(0.0785)	(0.0894)	(0.0603)
g9	-0.0965	-0.3161***	-0.2505***	-0.0904
	(0.0625)	(0.0794)	(0.0912)	(0.0612)
g10	-0.1894***	-0.4117***	-0.3203***	-0.1948***
	(0.0622)	(0.0786)	(0.0905)	(0.0609)
g11	-0.1895***	-0.3794***	-0.2876***	-0.1814***
	(0.0615)	(0.0770)	(0.0903)	(0.0598)
g12	-0.1126*	-0.2996***	-0.2480***	-0.1465**
	(0.0615)	(0.0748)	(0.0902)	(0.0594)
g13	-0.0941	-0.2958***	-0.2278**	-0.1408**
	(0.0614)	(0.0752)	(0.0891)	(0.0592)
g14	-0.1276*	-0.2887***	-0.2049**	-0.1100*
	(0.0674)	(0.0747)	(0.0888)	(0.0591)
g15	-0.0644	-0.2762***	-0.2091**	-0.1050*
	(0.0612)	(0.0747)	(0.0891)	(0.0588)
g16	-0.0417	-0.2429***	-0.1981**	-0.0914
	(0.0607)	(0.0753)	(0.0899)	(0.0602)
g17	0.0539	-0.1587**	-0.0621	0.0001
	(0.0609)	(0.0730)	(0.0864)	(0.0588)
g18	0.1160**	-0.0546	0.0771	0.0943*
	(0.0589)	(0.0722)	(0.0804)	(0.0554)
g19	0.1405***	-0.0020	0.1367*	0.1080**
	(0.0539)	(0.0686)	(0.0749)	(0.0531)
g20	0.0991**	0.0433	0.1543**	0.0898*
	(0.0493)	(0.0642)	(0.0709)	(0.0507)
g21	0.1551***	-0.0408	0.2095***	0.1031**
	(0.0472)	(0.1114)	(0.0662)	(0.0484)
g22	0.1448***	0.0474	0.0790	0.1316***
	(0.0473)	(0.0605)	(0.0922)	(0.0438)
g23	0.0990**	-0.0150	0.0016	0.0765*
	(0.0441)	(0.0550)	(0.0599)	(0.0410)

N	9375	10291	10401	10517
R^2	0.5354	0.4684	0.4072	0.5139
Log-likelihood	-40834.13	-46311.06	-45952.76	-45339.48
LR test chi2(23)	466.19	660.98	647.02	507.90
P-value	0.0000	0.0000	0.0000	0.0000
AIC	81720.27	92674.12	91957.52	90730.97
BIC	81906.06	92862.34	92146.01	90919.75

Table reports Non Linear Square estimates of four separate regressions. The dependent variable is pollutant $[NO_2]$ (μg/m^3). All the specifications correspond to the equation $[NO2]_t = k_1 + k_2\, traffic_t / ws_t^{\sum_{i=0}^{23} g_i h_i} + \varepsilon_t$. *traffic* is the total traffic in four lanes, *ws* is wind speed and h_i is a variable indicator for the hour of the day *i*. Standard errors, in parentheses, are heteroskedasticity and autocorrelation-consistent (HAC) standard errors using Newey-West's estimator for 24 lags. In the LR test, each specification is compared with the nested model $[NO2]_t = k_1 + k_2\, traffic_t / ws_t^{k_3} + \varepsilon_t$ under the null hypothesis. Estimates marked * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3: [PM_{10}] by season

	[PM_{10}] Winter	[PM_{10}] Spring	[PM_{10}] Summer	[PM_{10}]Autumn
k1	7.8883***	23.0488***	18.1928***	10.5288***
	(2.1699)	(2.8694)	(0.8098)	(1.5412)
k2	0.0497***	0.0632***	0.0196***	0.0270***
	(0.0158)	(0.0084)	(0.0020)	(0.0026)
g0	0.6211***	0.8588***	1.0229***	0.5986***
	(0.1107)	(0.1118)	(0.1557)	(0.1035)
g1	1.9953***	0.0085	-0.1161	-0.0034
	(0.3509)	(0.1647)	(0.1445)	(0.0938)
g2	1.4370***	-0.1551	0.2593*	-0.0343
	(0.3033)	(0.1149)	(0.1389)	(0.1322)
g3	2.5280***	0.0066	0.1052	0.1828
	(0.6695)	(0.1863)	(0.1947)	(0.1606)
g4	2.9688**	-0.0389	0.2787	0.2534
	(1.4304)	(0.3206)	(0.3297)	(0.3971)
g5	-0.1439	0.2630	0.1446	0.3260
	(0.1843)	(0.5117)	(0.3020)	(0.4588)
g6	-0.0383	-0.1919	-0.0818	0.3531
	(0.1518)	(0.1615)	(0.1796)	(0.2730)
g7	0.1996	-0.3753***	-0.5269***	0.0034
	(0.2094)	(0.1196)	(0.1404)	(0.0773)
g8	0.1570	-0.2990**	-0.6811***	-0.0268
	(0.1635)	(0.1325)	(0.1542)	(0.0905)
g9	0.1418	-0.3588***	-0.6626***	-0.0523
	(0.1550)	(0.1359)	(0.1557)	(0.0944)
g10	0.0273	-0.4696***	-0.6734***	-0.1534*
	(0.1565)	(0.1315)	(0.1551)	(0.0931)
g11	-0.0379	-0.5523***	-0.5785***	-0.1758*
	(0.1654)	(0.1247)	(0.1571)	(0.0934)
g12	-0.0772	-0.4891***	-0.5340***	-0.1620*
	(0.1614)	(0.1241)	(0.1497)	(0.0939)
g13	-0.0694	-0.4984***	-0.4633***	-0.1919**
	(0.1870)	(0.1238)	(0.1487)	(0.0960)
g14	-0.1563	-0.5217***	-0.4177***	-0.1842**
	(0.1454)	(0.1242)	(0.1468)	(0.0938)
g15	-0.0829	-0.4938***	-0.4025***	-0.1357
	(0.1803)	(0.1225)	(0.1474)	(0.0932)
g16	-0.0324	-0.4261***	-0.3417**	-0.0677
	(0.1730)	(0.1217)	(0.1469)	(0.0944)
g17	0.0304	-0.3306***	-0.2392*	0.0066
	(0.1662)	(0.1188)	(0.1444)	(0.0924)
g18	0.0891	-0.2559**	-0.0916	0.0797
	(0.1519)	(0.1152)	(0.1385)	(0.0882)
g19	0.0874	-0.2222**	0.0146	0.1084
	(0.1436)	(0.1133)	(0.1320)	(0.0860)
g20	0.1245	-0.1650	0.0404	0.0467
	(0.2386)	(0.1069)	(0.1287)	(0.0746)
g21	0.0740	-0.0622	0.1178	0.0718
	(0.1362)	(0.0965)	(0.1236)	(0.0651)
g22	0.0894	0.0017	-0.1331	0.0813
	(0.1039)	(0.0897)	(0.1852)	(0.0548)
g23	-0.0164	0.0840	-0.0579	0.0315
	(0.1064)	(0.0763)	(0.1121)	(0.0456)

N	9522	9860	10351	10467
R^2	0.1183	0.1959	0.2092	0.2650
Log-likelihood	-52631	-54755.74	-43058.89	-46627.94
LR test chi2(23)	82.42	192.44	477.45	154.32
P-value	0.0000	0.0000	0.0000	0.0000
AIC	105314	109563.5	86169.78	93307.89
BIC	105500.2	109750.6	86358.15	93496.54

Table reports Non Linear Square estimates of four separate regressions. The dependent variable is $[PM_{10}]$ (μg/m³). All the specifications correspond to the equation $[\mathrm{PM10}]_t = k_1 + k_2\, traffic_t / ws_t^{\sum_{i=0}^{23} g_i h_i} + \varepsilon_t$. *traffic* is the total traffic in four lanes, *ws* is wind speed and h_i is a variable indicator for the hour of the day *i*. Standard errors, in parentheses, are heteroskedasticity and autocorrelation-consistent (HAC) standard errors using Newey-West's estimator for 24 lags. In the LR test, each specification is compared with the nested model $[\mathrm{PM10}]_t = k_1 + k_2\, traffic_t / ws_t^{k_3} + \varepsilon_t$ under the null hypothesis. Estimates marked * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.