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Pricing local emission exposure of road traffic: An agent-based approach

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ABSTRACT

This paper proposes a new approach to iteratively calculate local air pollution exposure tolls in large-scale urban settings by taking the exposure times and locations of individuals into consideration. It explicitly avoids detailed air pollution concentration calculations and is therefore characterized by little data requirements, reasonable computation times for iterative calculations, and open-source compatibility. In a first step, the paper shows how to derive time-dependent vehicle-specific exposure tolls in an agent-based model. It closes the circle from the polluting entity, to the receiving entity, to damage costs, to tolls, and back to the behavioral change of the polluting entity. In a second step, the approach is applied to a large-scale real-world scenario of the Munich metropolitan area in Germany. Changes in emission levels, exposure costs, and user benefits are calculated. These figures are compared to a flat emission toll, and to a regulatory measure (a speed reduction in the inner city), respectively. The results indicate that the flat emission toll reduces overall emissions more significantly than the exposure toll, but its exposure cost reductions are rather small. For the exposure toll, overall emissions *in*crease for freight traffic which implies a potential conflict between pricing schemes to optimize local emission exposure and others to abate climate change. Regarding the mitigation of exposure costs caused by urban travelers, the regulatory measure is found to be an effective strategy, but it implies losses in user benefits.

Introduction

Problem statement

Negative externalities in the transport sector are known to lead to market inefficiencies and social welfare losses. The latter exist since individuals base their decisions on marginal private and not on marginal social costs, typically yielding demand levels beyond the economic optimum. To correct for these market failures, Pigou (1920) proposed to internalize the difference between marginal social costs and generalized prices by a toll. Since then, the concept has been studied widely in the transportation economic literature (see, e.g., Lindsey and Verhoef, 2000; Small and Verhoef, 2007; Vickrey, 1969; Arnott et al., 1993; Friesz et al., 2004). However, all these studies focus on congestion costs. Other important contributions to the total external costs are found to be air pollution, accidents, and noise (Maibach et al., 2008; Parry and Small, 2005).

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Since these environmental externalities have gained more attention over the last decades (OECD, 2006), and some studies find their impact for some regions at the same level as congestion costs (see, e.g., Creutzig and He, 2009), a new approach was proposed by Kickhöfer and Nagel (2013) to calculate vehicle-specific time-dependent air pollution tolls that reflect marginal emission costs with respect to congestion and vehicle attributes. However, their tolls did not account for population exposure; this drawback is tackled in the present paper.

Other possibilities to correct for these market failures are discussed in the literature, e.g. so-called backcasting approaches (Geurs and van Wee, 2004; IWW et al., 1998). The idea is to define threshold values based on medical studies, and then to derive avoidance costs in order to reach the desired values. The advantage is that avoidance costs are relatively easy to estimate. However, the definition of threshold values remains rather unclear, and exposure or concentration–response relationships could potentially provide more realistic information since they provide damage cost estimates (WHO Europe, 2006). For the European Union (Holland et al., 2005; Hurley et al., 2005) and the United States (U.S. EPA, 2011), this exposure approach typically consists of five steps:

1. Modeling exhaust emissions.
2. Modeling emission dispersion.
3. Deriving air pollution concentration.
4. Estimating exposure of individuals to air pollutants with respect to special population groups like pregnant or ill persons, children and elderly.
5. Applying concentration–response functions yielding numbers of cases for mortality, life years lost, hospital admissions, premature mortality, minor restricted activity days, work loss days, etc.
6. Assigning monetary values to each of these cases.

Emission dispersion and air quality models

In the literature, a large number of microscopic and macroscopic dispersion models exists. However, as a review paper by Holmes and Morawska (2006) shows, the latter cannot provide the spatial resolution that is needed for air pollution concentration modeling within urban-scale scenarios. The former are generally characterized by long computing times and are therefore often not applicable to large-scale urban regions. According to Holmes and Morawska (2006), most emission dispersion and air quality modeling tools need geographical and meteorological input data like temperature, altitude, humidity, cloud cover, peak sun, sunrise, terrain elevation data, land cover data, hourly meteorological data, sea and land breezes. These data might not be available for the area of interest.

Despite these data requirements, there exist several attempts to model air quality in urban regions. Hatzopoulou and Miller (2010) use the open-source modeling tool CALPUFF-CALMET to evaluate air quality. Calculation of concentration values for 15,000 cells and 62,500 receptors from link-wise aggregated exhaust emissions initially takes them 190 h of computing time. Hence, such approach would simply not be manageable for the iterative calculation of toll levels as it is attempted in the present paper. The Community Multiscale Air Quality model (CMAQ) and EPA's Modeled Attainment Test Software used by U.S. EPA (2011) have their focus on North American scenarios. When applying the models to European scenarios, Appel et al. (2012) find Particular Matter ($PM_{2.5}$) concentration values to be underestimated by 24–65%. Holland et al. (2005) use the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) combined with Regional Air Pollution Information and Simulation (RAINS) on a 50×50 km grid. However, both tools focus on macroscopic long-range dispersion over whole countries. Hülsmann et al. (2013) focus on emission dispersion modeling for street canyons using the Operational Street Pollution Model (OSPM) for a small area of their scenario. Despite the model's complexity and relatively large data requirements, the authors managed to derive air pollution concentrations and time-dependent tolls in order to eliminate emission hotspots in the small research area. Unfortunately, the software is not open-source, and can therefore not be integrated into the transport simulation MATSim[1] for iterative toll calculations.

Simplified approach

This paper aims at internalizing air pollution exposure costs, i.e. pricing damages to human health in an agent-based transport model with activity-based demand. This requires the development of a new approach to iteratively calculate local air pollution exposure tolls in large-scale urban settings by taking the exposure times and locations of individuals into consideration. As discussed in section 'Emission dispersion and air quality models', none of the emission dispersion models presented there is suitable for such attempt. Thus, the new approach – for now – needs to avoid detailed air pollution concentration calculations and should be characterized by little data requirements, reasonable computation times, and open-source compatibility. As will be discussed later in this paper (section 'Discussion'), this also implies some limitations. However, the strengths of the approach lie in the computational performance and in translating the activity and travel patterns of the activity-based demand into individual toll levels. The approach is composed of the following three steps:

[1] 'Multi-Agent Transport Simulation', see www.matsim.org.