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Marginal costs of freeway traffic congestion with on-road pollution exposure externality

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ABSTRACT

The health cost of on-road air pollution exposure is a component of traffic marginal costs that has not previously been assessed. The main objective of this paper is to introduce on-road pollution exposure as an externality of traffic, particularly important during traffic congestion when on-road pollution exposure is highest. Marginal private and external cost equations are developed that include on-road pollution exposure in addition to time, fuel, and pollution emissions components. The marginal external cost of on-road exposure includes terms for the marginal vehicle's emissions, the increased emissions from all vehicles caused by additional congestion from the marginal vehicle, and the additional exposure duration for all travelers caused by additional congestion from the marginal vehicle. A sensitivity analysis shows that on-road pollution exposure can be a large portion (18%) of marginal social costs of traffic flow near freeway capacity, ranging from 4% to 38% with different exposure parameters. In an optimal pricing scenario, excluding the on-road exposure externality can lead to 6% residual welfare loss because of sub-optimal tolls. While regional pollution generates greater costs in uncongested conditions, on-road exposure comes to dominate health costs on congested freeways because of increased duration and intensity of exposure. The estimated marginal cost and benefit curves indicate a theoretical preference for price controls to address the externality problem. The inclusion of on-road exposure costs reduces the magnitudes of projects required to cover implementation costs for intelligent transportation system (ITS) improvements; the net benefits of road-pricing ITS systems are increased more than the net benefits of ITS traffic flow improvements. When considering distinct vehicle classes, inclusion of on-road exposure costs greatly increases heavy-duty vehicle marginal costs because of their higher emissions rates and greater roadway capacity utilization. Lastly, there are large uncertainties associated with the parameters utilized in the estimation of health outcomes that are a function of travel pollution intensity and duration. More research is needed to develop on-road exposure modeling tools that link repeated short-duration exposure and health outcomes.

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1. Introduction

The total costs of traffic congestion are large, with estimates in the hundreds of billions of dollars annually for the US (Schrank and Lomax, 2009a). Not only are the total costs of congestion large, they are economically inefficient because of external costs – a feature of traffic congestion that is well established (Santos et al., 2010; Small and Verhoef, 2007; Walters, 1961). Capacity-based congestion management addresses roadway supply and aims to reduce the costs of traffic congestion by

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increasing physical roadway lane miles or increasing vehicle throughput from existing roadways using intelligent transportation systems (ITS) or other tools that improve traffic efficiency (ITS Joint Program Office, 2011). These methods typically fail to address the externality problem, and so while they can reduce total costs, the resulting travel volumes are still inefficiently high. Alternatively, travel demand and traffic management can reduce the travel volume to a socially optimal level (i.e. maximizing total net benefit) through traffic volume controls (such as travel restrictions) or price controls (such as congestion/roadway charges or tolls).

Economic assessments of externalities from road travel include the costs of air pollution emissions, noise, space consumption, fuel consumption, vehicle maintenance, road maintenance, and other dimensions (Bickel et al., 2006; Delucchi and McCubbin, 2010; Delucchi, 2000; Lemp and Kockelman, 2008; Maibach et al., 2007; Mayeres et al., 1996; Ozbay et al., 2007; Parry et al., 2007; Santos et al., 2010). Time is usually the largest single cost component, but the estimation of other costs is important for the development of roadway pricing systems that aim to internalize the external costs of transportation (Macharis et al., 2010). The external costs of traffic congestion are unique in that they are not static external costs per vehicle mile of travel. Congestion externalities are sometimes calculated as external time costs alone (Bickel et al., 2006; De Borger and Wouters, 1998; Proost and Dender, 2008), though estimates of marginal congestion costs have included other externalities, often in the context of roadway pricing (HDR, 2009; Holguín-Veras and Cetin, 2009; Johansson, 1997; Shepherd, 2008). In order to estimate emissions-related congestion externalities, modeled emissions rates must be at least a function of speed (Johansson, 1997).

The human health costs of exposure to vehicle emissions for a regional population have previously been quantified as an externality of congestion. What has not been considered as a component of marginal congestion costs is the health impact of in-vehicle pollution exposure for travelers. In a study of congestion costs Bilbao-Ubillos (2008) notes that "it may be advisable to distinguish between various levels of exposure to environmental externalities", but decides that insufficient data are available to determine exposure differences. In-vehicle pollution exposure, because of the high concentrations found on roadways, can be a significant portion of people's daily exposure (Fruin et al., 2008). Beyond the high exposure concentrations due to proximity to vehicle emissions, on-road exposure is distinct from regional exposure because it is a function of travel duration in addition to the quantity of vehicle emissions. Each additional vehicle increases other travelers' on-road exposure costs by increasing both emissions levels and travel time, which in turn increase exposure concentrations and exposure duration respectively.

The main objective of this paper is to introduce on-road in-vehicle pollution exposure as an externality of traffic congestion. Marginal cost equations for freeway traffic are presented, followed by a discussion of parameter estimation and a case study of Portland, Oregon. This paper also analyzes whether price or quantity controls is best to achieve optimal traffic volumes. Policy implications of the exposure externality for traffic management systems and vehicle class-specific pricing are also discussed. The next section develops the necessary traffic models and cost equations.

2. Methodology

In this section total and marginal cost components are presented, followed by identification of the functional forms used in this paper. Freeway congestion is modeled using a time-averaged speed-flow relationship for a corridor, with travel demand in number of vehicle trips on the corridor per unit time as the output measure.

2.1. Social costs and benefits in traffic

The total social cost (TSC) of freeway travel considered here is composed of time, fuel, pollution emissions, and on-road exposure components. This scope does not include all possible dimensions of the externality problem (it excludes crash costs and noise, for example). But it does include the major components that are expected to be a function of vehicle speed (as opposed to cost components that are per-mile), to capture the impacts of congestion (where speed is a function of the travel volume). Thus, only short run marginal costs are included (i.e. variable costs related to each additional vehicle); long run marginal costs related to infrastructure are neglected.

Expressed as a function of the travel demand volume q (in vehicles per hour per lane, or vphpl), TSC is

$$TSC(q) = lq\left\{c_t t(q) + c_f f(q) + \sum_p \left[c_{e,p} e_p(q)\right] + \sum_p \left[c_{h,p} I_p(q)\right]\right\} \tag{1}$$

in \$ per hour, where l is the size of the roadway corridor under study (lane miles), $t(q)$ is the travel rate (hours per mile), $f(q)$ is the fuel consumption rate (gallons per vehicle mile), $e_p(q)$ is the emissions rate of pollutant p (kg per vehicle mile), $I_p(q)$ is the intensity of on-road exposure to pollutant p (person hour mg/m^3 per veh mile), and c_t, c_f, $c_{e,p}$, and $c_{h,p}$ are the unit costs of time, fuel, emissions, and exposure, respectively, in \$ per vehicle hour, \$ per gallon, \$ per kg, and \$ per person hour mg/m^3. Pollution emissions unit costs ($c_{e,p}$) include all impacts of emissions other than exposure for travelers on the same roadway (near-road and regional health impacts, visibility, crop effects, etc.). The total social benefit (TSB) is also a function of q, expressed as the area under the marginal benefit (demand) curve in \$ per hour

$$TSB(q) = l\int_0^q \beta(q)\mathrm{d}q, \tag{2}$$

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