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

Alexander Y. Bigazzi [*], Miguel A. Figliozzi [1]

Portland State University, Department of Civil and Environmental Engineering, P.O. Box 751, Portland, OR 97207-0751, USA

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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

* Corresponding author. Tel.: +1 503 725 4282; fax: +1 503 725 5950.
  E-mail addresses: abigazzi@pdx.edu (A.Y. Bigazzi), figliozzi@pdx.edu (M.A. Figliozzi).
[1] Tel.: +1 503 725 4282; fax: +1 503 725 5950.

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

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

where $\beta(q)$ is the marginal benefit of travel in $ per vehicle mile. For convenience, the variables in these cost equations are summarized in Table 1.

The marginal social costs (MSC) are found by differentiating Eq. (1):

$$MSC(q) = \frac{\partial TSC(q)}{\partial q}$$

$$MSC(q) = l \left\{ \begin{array}{l} c_t[t(q) + qt'(q)] + c_f[f(q) + qf'(q)] \\ + \sum_p [c_{e,p}e_p(q) + qc_{e,p}e_p'(q)] + \sum_p [c_{h,p}I_p(q) + qc_{h,p}I_p'(q)] \end{array} \right\} \qquad (3)$$

in $ per vehicle/lane,[2] where $t'(q) = \frac{\partial t(q)}{\partial q}$ and so forth. Subdividing the total marginal social costs as marginal private costs (MPC) and marginal external costs (MEC), both in $ per vehicle/lane,

$$MPC(q) = l \left\{ c_t t(q) + c_f f(q) + \sum_p [c_{h,p}I_p(q)] \right\} \qquad (4)$$

includes the marginal travelers' time, fuel, and health costs of on-road exposure, and

$$MEC(q) = l \left\{ c_t q t'(q) + c_f q f'(q) + \sum_p \left[c_{e,p}e_p(q) + qc_{e,p}e_p'(q) \right] + q \sum_p \left[c_{h,p}I_p'(q) \right] \right\} \qquad (5)$$

is all other social costs. Further subdividing, all marginal cost terms can be separated into time, fuel, pollution emissions, and health costs of on-road exposure components, based on their cost coefficients. Table 2. shows these private and external marginal cost components, where the subscripts $t, f, e,$ and h denote time, fuel, pollution emissions, and on-road exposure health costs, respectively. We also designate the marginal traveler's perceived costs, assumed to be only the time and fuel components (Ozbay et al., 2007), as

$$MPC_{t+f}(q) = MPC_t(q) + MPC_f(q). \qquad (6)$$

This distinction is made with the consideration that although health costs of on-road exposure for the marginal traveler are internal, it is likely that the typical marginal traveler is not accounting for them in travel decision-making because, for example, the marginal traveler is unaware of on-road exposure costs or cannot quantify them. Thus, private equilibrium will be expected based on MPC_{t+f}, not MPC.

The marginal benefits at q are

$$MB(q) = \frac{\partial TSB(q)}{\partial q} = l\beta(q), \qquad (7)$$

again in $ per vehicle per lane. We assume an inverse demand function, $\frac{\partial \beta(q)}{\partial q} \leqslant 0$, with a shape that reflects constant demand elasticity to costs. The elasticity of q to β is

$$\eta_q^\beta = \frac{\beta(q)}{q} \frac{\partial q}{\partial \beta(q)}, \qquad (8)$$

estimable from the economic literature.[3] From Eq. (8),

$$\beta(q) = \gamma \cdot \exp\left(\frac{\ln q}{\eta_q^\beta}\right), \qquad (9)$$

where γ is a constant. By assuming an observed equilibrium volume at $MB(q) = MPC_{t+f}(q)$, the marginal benefit curve can be drawn from an estimate of γ as

$$\gamma = \frac{MPC_{t+f}(q)}{l} \exp\left(\frac{-\ln q}{\eta_q^\beta}\right). \qquad (10)$$

The net social benefit at volume q is $NB(q) = TSB(q) - TSC(q)$, which is maximized when $MB(q) = MSC(q)$. Denoting this socially optimal volume q^*, the optimal road charge or tax is the marginal external cost at q^* – the Pigouvian toll (Small and Verhoef, 2007).

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[2] In reduced form the marginal cost units are $\frac{\text{lane}}{\text{vehicle}}$, though perhaps more intuitively they are in $ per $\frac{\text{vehicle}}{\text{lane}}$.

[3] Common elasticities of vehicle travel demand to travel costs are in the range of −0.2 to −0.7 (Goodwin et al., 2004; Maibach et al., 2007; Noland and Lem, 2002; Small and Verhoef, 2007).

Table 1
Social cost equation variables.

Variable	Unit	Definition
l	Lane miles	Size of the roadway corridor under study
q	Vehicles per hour per lane (vphpl)	Travel demand volume
$t(q)$	hours per vehicle mile	Travel rate
$f(q)$	gallons per vehicle mile	Fuel consumption rate
$e_p(q)$	kg per vehicle mile	Emissions rate of pollutant p
$I_p(q)$	person hour mg/m^3 per veh mile	Intensity of on-road exposure to pollutant p
c_t	\$ per vehicle hour	Unit cost of time
c_f	\$ per gallon	Unit cost of fuel
$c_{e,p}$	\$ per kg	Unit cost of emissions of pollutant p
$c_{h,p}$	\$ per person hour mg/m^3	Unit health cost of exposure to pollutant p
$\beta(q)$	\$ Per vehicle mile	Marginal benefit of travel

Table 2
Definition of marginal cost components.

MSC (Marginal Social Cost)	MPC (Marginal Private Cost)			
		MPC_t	Time cost	$lc_t t(q)$
		MPC_f	Fuel cost	$lc_f f(q)$
		MPC_h	Health cost of on-road exposure	$l\sum_p [c_{h,p} I_p(q)]$
	MEC (Marginal External Cost)	MEC_t	Time cost	$lc_t\, qt'(q)$
		MEC_f	Fuel cost	$lc_f qf'(q)$
		MEC_e	Regional pollution cost of emissions	$l\sum_p \left[c_{e,p} e_p(q) + qc_{e,p} e_p'(q)\right]$
		MEC_h	Health cost of on-road exposure	$lq\sum_p \left[c_{h,p} I_p'(q)\right]$

2.2. On-road pollution exposure

The on-road pollution exposure intensity $I(q)$ is a function of the on-road emissions and travel rate, among other factors. The average in-vehicle concentration of pollutant p (in mass per unit volume) can be estimated as $\left[q \cdot n \cdot e_p(q) \cdot \frac{P_p}{D_p}\right]$, where n is the number of lanes, P_p is the vehicle penetration of pollutant p expressed as a ratio of the in-vehicle to out-vehicle pollution concentrations (no units), and D_p is a dispersion parameter (pollutant dispersion perpendicular to the roadway as area per unit time). The personal exposure intensity to pollutant p in person-time-concentration per vehicle mile is then

$$I_p(q) = O \cdot t(q) \cdot q \cdot n \cdot e_p(q) \cdot \frac{P_p}{D_p}, \tag{11}$$

where O is the average vehicle occupancy (persons/vehicle) and $t(q)$ is the travel rate defined above. Assuming P_p and D_p are fixed parameters with respect to q, if D_p is in units of m^2/s then Eq. (11) simplifies with a new parameter K_p, where

$$K_p = \frac{nOP_p}{D_p}\left[\frac{1 \text{ mile}}{1609 \text{ m}} \frac{10^6 \text{ mg}}{\text{kg}} \frac{1 \text{ h}}{3600 \text{ s}}\right] \tag{12}$$

in $\frac{\text{ln person h mile mg}}{\text{veh m}^3 \text{ kg}}$. Then,

$$I_p(q) = K_p \cdot q \cdot t(q) \cdot e_p(q) \tag{13}$$

in person hour mg/m^3 per veh mile. The value of K_p will depend on a number of factors (meteorology and vehicle type, for example), but is considered exogenous to congestion level or q. Differentiating Eq. (13),

$$I_p'(q) = K_p\left\{q \cdot t(q) \cdot e_p'(q) + q \cdot t'(q) \cdot e_p(q) + t(q) \cdot e_p(q)\right\}. \tag{14}$$

Eqs. (13) and (14) can be substituted into the preceding marginal cost equations containing $I_p(q)$ or $I_p'(q)$ in order to define marginal health costs using the time and emissions rate functions $t(q)$ and $e_p(q)$. Thus, from Table 2 the on-road exposure health costs are

$$MPC_h(q) = lqt(q)\sum_p [c_{h,p} K_p e_p(q)] \text{ and} \tag{15}$$

$$MEC_h(q) = lq\sum_p \left[c_{h,p} K_p\left\{qt(q)e_p'(q) + qt'(q)e_p(q) + t(q)e_p(q)\right\}\right]. \tag{16}$$

The three terms in brackets in Eq. (16) represent the marginal change in on-road exposure due to: (1) the increased emissions from all vehicles caused by additional congestion from the marginal vehicle, (2) the additional exposure duration for all travelers caused by additional congestion from the marginal vehicle, and (3) the marginal vehicle's emissions.

2.3. Functional forms for time, fuel, and emissions rates

The functional form used for $t(q)$ is the well-known Bureau of Public Roads (BPR) function (Bureau of Public Roads, 1964; Small and Verhoef, 2007). This is a static, time-averaged model of roadway performance with parameters of a and b (unitless), the free-flow travel rate t_o (h/mile) and volume capacity q_c (vphpl)[4]:

$$t(q) = t_o\left(1 + a\left(\frac{q}{q_c}\right)^b\right). \tag{17}$$

Differentiating,

$$t'(q) = \frac{t_o a b}{q_c^b} q^{b-1}.$$

Emissions rates for pollutant p are drawn from previous emissions research (Bigazzi and Figliozzi, 2012a) using the form

$$e_p(q) = \exp\left(\sum_{i=0}^{4} a_{i,p} t(q)^{-i}\right), \tag{18}$$

which makes use of $t(q)$ from Eq. (17). Differentiating with respect to q,

$$e'_p(q) = \exp\left(\sum_{i=0}^{4} a_{i,p} t(q)^{-i}\right) \cdot \sum_{i=1}^{4}(-i a_{i,p} t(q)^{-i-1}) \cdot t'(q).$$

Fuel consumption rates are based on the strong association between greenhouse gas emissions and fuel consumption. Using an assumed relationship of 10 kg CO_2e per gallon of fuel (US Environmental Protection Agency, 2005), $f(q)$ in gallons per vehicle mile is

$$f(q) = e_{CO_2 e}(q)/10, \tag{19}$$

and $f'(q) = e'_{CO_2 e}(q)/10$.

2.4. Price versus quantity control

One of the objectives of this paper is to compare price and quantity controls for optimizing freeway traffic volume with regard to net social benefits. With deterministic, known costs and benefits, price and quantity controls are theoretically equivalent. With stochastic or uncertain costs and benefits there is differential risk in applying each instrument incorrectly. From a classic paper by Weitzman (1974), the "comparative advantage" of price over quantity controls, assuming independently distributed costs and benefits, is assessed by the parameter

$$\Delta = \frac{\sigma^2(MB' + MSC')}{2 \cdot MSC'^2}, \tag{20}$$

where σ^2 is the expected variance (mean square error) in MSC and MB' and MSC' are differentiated with respect to q; i.e. $MB' = \frac{\partial MB}{\partial q} = l\beta'(q) = \frac{l\gamma}{q\eta_q^\beta}\exp\left(\frac{\ln q}{\eta_q^\beta}\right)$. A positive Δ favors a price control (e.g. tax or toll), while a negative Δ favors quantity control (e.g. traffic control measures). Conveniently, the sign of Δ is simply the sign of $MB' + MSC'$ (which does not require estimation of σ^2). The magnitude of the comparative advantage increases with σ^2. Using a stochastic model of traffic flow breakdown where there is a greater likelihood of queue formation near roadway capacity q_c (Brilon et al., 2007), we expect σ^2 to increase as the volume q approaches q_c because of the uncertainty of costs (Bigazzi and Figliozzi, 2011).

3. Parameter estimates

The previous section presented marginal costs as functions of q considering the components of time, fuel, pollution emissions, and on-road pollution exposure. This section describes parameter values selected for a case study of congested freeway costs in Portland, Oregon. The results of applying those parameter values are presented in the following section.

The case study analysis assumes a 3-lane freeway and calculates costs per lane mile (ln mile) of roadway. Selected parameter and unit cost estimates are shown in Table 3, along with reference sources. "Medium Cost" parameter values are assumed initially, and the "Low Cost" to "High Cost" range is tested below for sensitivity analysis. All prices are in 2011 US$, adjusted using the annual average urban Consumer Price Index from the US Bureau of Labor Statistics.[5] Unit time costs (c_t) are estimated for a volume-weighted average vehicle, including business travel and freight. Emissions and health unit costs

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[4] We do not adjust for passenger-car equivalency, assuming $\frac{q}{q_c}$ is unaffected by units of vehicles or "passenger car equivalents".
[5] ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt.

Table 3
Case study parameters.

Parameter	Low cost	Medium cost	High cost	Units	Definition	Sources
η_q^β	−0.2	−0.5	−0.7	–	Elasticity of travel demand volume q to marginal benefit of travel β	Goodwin et al. (2004), Maibach et al. (2007), Noland and Lem (2002), Small and Verhoef (2007)
D_p	11	9	7	m^2/s	Dispersion parameter for pollutant p	Bigazzi et al. (2013)
P_p	0.2	0.8	1.0	–	Vehicle penetration factor for pollutant p	Hudda et al. (2011), Xu and Zhu (2009)
O	1	1.2	2	persons/veh	Vehicle occupancy	Federal Highway Administration (2005)
c_t	10	20	40	\$/veh hour	Vehicle travel time unit cost	Federal Highway Administration (2005), HDR (2009, 2008)
c_f	2	4	8	\$/gal	Fuel unit cost	Assumed
c_{e,CO_2e}	0.01	0.023	0.07	\$/kg	Regional pollution unit cost for greenhouse gas emissions	Delucchi (2000), HDR (2009), National Research Council (2010)
$c_{e,CO}$	0.14	0.37	0.60	\$/kg	Regional pollution unit cost for carbon monoxide emissions	Federal Highway Administration (2005), HDR (2009)
$c_{e,PM_{2.5}}$	6.26	75.76	372.19	\$/kg	Regional pollution unit cost for fine particulate matter emissions	Delucchi (2000), Federal Highway Administration (2005), Litman (2009), Muller and Mendelsohn (2007)
c_{e,NO_x}	2.94	14.54	40.38	\$/kg	Regional pollution unit cost for nitrogen oxides emissions	Delucchi (2000), Federal Highway Administration (2005), HDR (2009), Litman (2009), Ozbay et al. (2007), Small and Kazimi (1995)
$c_{e,HC}$	2.86	12.91	19.86	\$/kg	Regional pollution unit cost for gaseous hydrocarbon emissions	Federal Highway Administration (2005), HDR (2009), Litman (2009), Small and Kazimi (1995)
c_{h,CO_2e}	0	0	0	\$/ person hour mg/m^3	Health unit cost for greenhouse gas on-road pollution exposure	Assumed
$c_{h,CO}$	0.05	0.14	0.33	\$/ person hour mg/m^3	Health unit cost for carbon monoxide on-road pollution exposure	Burnett et al. (1998)
$c_{h,PM_{2.5}}$	3.29	16.46	32.92	\$/ person hour mg/m^3	Health unit cost for fine particulate matter on-road pollution exposure	Brunekreef et al. (2009), Pope and Dockery (2006), Pope et al. (2002)
c_{h,NO_x}	3.29	26.34	32.92	\$/ person hour mg/m^3	Health unit cost for nitrogen oxides on-road pollution exposure	Brunekreef et al. (2009), Nafstad et al. (2004)
$c_{h,HC}$	0	0	0	\$/ person hour mg/m^3	Health unit cost for gaseous hydrocarbon on-road pollution exposure	Could not be determined

are for five pollutants, p: greenhouse gases (CO_2e), carbon monoxide (CO), fine particulates ($PM_{2.5}$), nitrogen oxides (NO_x), and hydrocarbons (HC). The emissions unit costs ($c_{e,p}$) are for atmospheric pollution, excluding the health effects of on-road exposure for the traffic stream under study (assumed to be a negligible component of existing pollution cost estimates). Literature on VOC (volatile organic compound) emissions cost estimates are applied for HC unit cost $c_{e,HC}$ because of availability.

Unit cost estimates for on-road pollution exposure ($c_{h,p}$) are less readily available than for regional pollution $c_{e,p}$. Greenhouse gases (CO_2e) are assumed to have no health impact through on-road exposure. Other pollutant on-road exposure unit costs are estimated based on a relative risk of mortality from long-term ambient exposures. On-road pollution exposure is assumed to be a short-duration repeated event with health implications directly proportional to the duration and intensity of exposure. A baseline mortality cost of \$3.29/person hour is used, computed from \$7.4 million per statistical life and a US annual all-cause working-age mortality rate of 0.39%, following (Grabow et al., 2012). The values of $c_{h,p}$ in Table 3 for CO, $PM_{2.5}$, and NO_x are then computed using estimates from the epidemiology literature of changes in relative risk of all-cause mortality with changes in ambient exposure concentration. The "Medium" value estimates of $c_{h,p}$ in Table 3 use mortality risk increases of 4.2% per mg/m^3 increase in CO exposure concentration (Burnett et al., 1998), 0.5% per µg/m^3 increase in $PM_{2.5}$ (Pope and Dockery, 2006), and 0.8% per µg/m^3 increase in NO_x(Nafstad et al., 2004). The value ranges in Table 3 come from the same literature, as well as (Brunekreef et al., 2009; Pope et al., 2002). A lack of applicable studies prevents similar $c_{h,p}$ estimates for HC exposure, so it is not included in the analysis.

This approach is conservative in that it excludes morbidity costs and uses a working-age mortality rate – but there is still much uncertainty in the unit cost estimates. The literature on health effects from traffic-related air pollution is epidemiological, addressing long-term health impacts from aggregate population exposure to ambient concentrations (Health Effects Institute, 2010). The economic costs of specific health outcomes have received much attention, but the health effects of exposure during daily travel (a repeated short-duration event in a high-concentration environment) have not. The ability to demonstrate causal relationships between exposure and health outcomes is more difficult on shorter time scales, as discussed in Pope and Dockery (2006). As with other research (Small and Kazimi, 1995), this analysis assumes linearly independent

health and pollution effects; as a consequence, interactions of pollutants for regional air quality (such as ozone formation) and potential interactive health impacts of concurrent exposures are neglected. Johan de Hartog et al. (2010) use a similar approach of applying epidemiological evidence to estimate the health effects of traveler exposure, with the caveat that the toxicity of traffic-related $PM_{2.5}$ concentrations may be higher than ambient $PM_{2.5}$.

The parameters necessary for calculating K_p are D_p, P_p, and O (Eq. (12)). Because K_p and D_p are inversely proportional (Eq. (12)), the "Low Cost" parameter values for D_p in Table 3 are numerically higher than the "High Cost" parameter values (i.e. greater dispersion leads to lower exposure costs). Using the values in Table 3, the low, medium, and high estimates of K_p are 0.0094, 0.0552, and 0.1480 in $\frac{\ln \text{ person h mile mg}}{\text{veh m}^3 \text{ kg}}$. The parameters D_p and P_p are assumed to be the same for all pollutants because of a lack of available pollutant-specific estimates. The assumed BPR function parameter values are $a = 0.83, b = 5.5, t_o = 1/60$ (i.e. 60 mile/h free-flow speed), and roadway capacity of $q_c = 2200$ vphpl (Horowitz, 1991). Emissions parameter estimates ($a_{i,p}$) for Eq. (18) are from Bigazzi and Figliozzi (2012a), who generated emissions rates using the MOVES motor vehicle emissions model (US Environmental Protection Agency, 2009) with a 2010 vehicle fleet from freeways in Portland, Oregon composed of 9% heavy-duty vehicles. The dispersion parameter estimates D_p are also taken from analysis of Portland area freeways (Bigazzi et al., 2013).

In order to derive the marginal benefit curve we estimate the parameter γ from an observed q by assuming equilibrium at $MB(q) = MPC_{t+f}(q)$ using Eq. (10). Observed average peak-period freeway traffic volumes for Portland are used as the equilibrium volume q. The estimated equilibrium q is 1,477 vphpl, calculated as the average hourly peak period freeway vehicle miles traveled divided by the number of freeway lane miles (extracted from the 2009 Urban Mobility Report (Schrank and Lomax, 2009a)). Thus, the emissions rates $e_p(q)$, dispersion parameter D_p, and equilibrium volume estimates comprise a case study for Portland area freeways. The next section presents marginal cost estimates and equilibrium analysis using these case study values, followed by sensitivity analysis to address parameter uncertainty and policy analysis looking at congestion mitigation strategies and the impacts of heavy-duty vehicles.

4. Results

For travel demand volumes q up to the roadway capacity of 2200 vphpl (q_c), the modeled average speed falls from 60 mile/h to 33 mile/h. The modeled average fuel efficiency falls from 23 to 20 mile/gal. Emissions rates are 10–61% higher at $q = q_c$ than in free-flow conditions, with the greatest percent increases for $PM_{2.5}$ and HC emissions rates. On-road exposure concentrations at capacity due to emissions from vehicles in the same direction of travel are estimated to be around 300, 5, 100, and 10 μg/m^3, respectively, for CO, $PM_{2.5}$, NO_x, and HC. These are at the low end of reported ranges for measured in-vehicle concentrations of CO and $PM_{2.5}$ (Kaur et al., 2007), which is to be expected because background concentrations and counter-flowing vehicle emissions are not included in the model.

4.1. Marginal costs

The estimated marginal cost components (Table 2) are shown in Fig. 1 for volumes q from 0 to 2200 vphpl. The costs are shown cumulatively as stacked areas, with marginal costs in $/h per ln mile for each additional vphpl, or simply $/veh mile on the corridor. As in Eq. (6), marginal external costs of time and fuel are combined as $MEC_{t+f} = MEC_t + MEC_f$. At low q the costs are predominantly MPC_{t+f} (private time and fuel costs), with a small external cost from pollution emissions (MEC_e) of $0.03/veh mile. Marginal social costs (MSC) at low volumes are around $0.50/veh mile and increase dramatically with q to $3/veh mile at capacity q_c. All cost components increase in congestion, but the largest increase is for external costs MEC (which is dominated by time costs.). Because MEC is also the Pigouvian tax, first-best congestion charges in Fig. 1 range from almost $0 to over $2/veh mile.
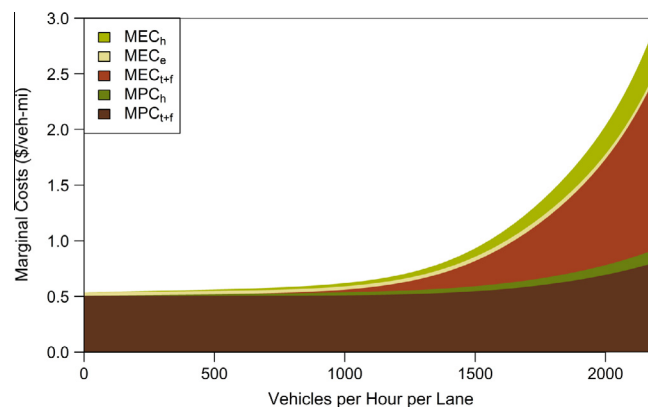

Fig. 1. Marginal cost estimates.

Fig. 2 shows the marginal cost components normalized to the full social costs MSC: each shaded area is the fraction of MSC from each cost component. Marginal private costs MPC decrease from 94% of MSC to only 31% at capacity q_c. The growth of externalities with congestion is clear: external exposure and time costs greatly increase at higher volumes. These effects are linked, as the travel time function is a component of the exposure externality (Eq. (16)). All marginal cost components increase in congestion (Fig. 1), but less so than MEC_h and MEC_t. The external pollution cost MEC_e shrinks in importance because of emissions rates that are less sensitive to speed than travel rates are sensitive to speed.

In terms of the different pollutants, CO_2e and NO_x dominate the pollution externality MEC_e with 33% and 42% of the costs, respectively, at high volumes. The shares change slightly with q because HC and $PM_{2.5}$ are more sensitive to congestion than the other pollutants. NO_x also dominates the exposure externality MEC_h: at q_c the estimated MEC_h due to CO, $PM_{2.5}$, and NO_x exposure are \$0.006, \$0.012, and \$0.42 per veh mile, respectively. In contrast, at q_c the pollution externality MEC_e is \$0.05/veh mile and time and fuel externalities are MEC_t = \$1.52/veh mile and MEC_f = \$0.06/veh mile, respectively. At q_c private costs are MPC_{t+f} = \$0.81/veh mile for time and fuel and MPC_h = \$0.12/veh mile for on-road exposure. The on-road exposure components of MPC_h and MEC_h are 4% and 14%, respectively, of MSC at q_c, showing the potential importance of considering the on-road exposure costs.

Estimated average (not marginal) pollution costs are around \$0.03/veh mile, and the average externality cost per vehicle mile at q_c is \$0.37/veh mile; both are within a reasonable range as reported in the externality literature (Delucchi and McCubbin, 2010; Lemp and Kockelman, 2008; Maibach et al., 2007). The dominance of NO_x in the pollution externality estimates (per vehicle mile) is consistent with some of the literature (Mayeres et al., 1996; Small and Kazimi, 1995), but others have found $PM_{2.5}$ costs per vehicle mile to be higher than NO_x costs (McCubbin and Delucchi, 1999; Muller and Mendelsohn, 2007). Some differences in cost estimates depend on how ambient pollution effects are apportioned to precursor emissions in the unit cost estimates. NO_x is a precursor to both tropospheric ozone and fine particulates, while NO_2 has direct human health impacts and in the short-term NO can provide benefits through ozone destruction. McCubbin and Delucchi (1999) found that NO_x was the largest vehicle-generated precursor of ambient particulate matter in southern California (though these high NO_x unit cost estimates might not apply outside of basin regimes such as in Los Angeles).

4.2. Marginal cost uncertainty

Turning now to the question of price versus quantity controls (or tolls versus traffic control), the estimated sign of the Weitzman parameter Δ is the sign of $MB' + MSC'$ (Eq. (20)). The value of MB' depends on the location of the demand curve (i.e. the parameter γ), but it generally is negative at low volumes q and then approaches 0 asymptotically with higher q. The MSC' curve starts at 0 at low q and increases non-linearly with q. Deriving γ from q by assuming $MB(q) = MPC_{t+f}(q)$, we can calculate that for equilibrium $q \geqslant 1348$ vphpl, Δ is positive at q. A positive Δ indicates a theoretical preference for price controls (tolls), with a stronger preference for larger absolute values (as expected around capacity q_c).

The sign of Δ around q_c (where it is largest) may not be positive for other locations of the MB curve. At q_c, Δ only becomes negative if the MB curve shifts sufficiently to the right, which occurs for equilibrium $q \geqslant 3253$ vphpl (an extremely high and unrealistic volume/capacity ratio of 1.5). These results suggest a general preference for price controls ($\Delta > 0$) over a wide range of q where severe real-world congestion takes place. With multiple units (travelers) possessing uncertain marginal social costs MSC, Δ will further increase (become more positive) with more units if the MSC are poorly correlated (Weitzman, 1974). Thus, heterogeneous costs (because of heterogeneous vehicle types or values of time, for example), will likely contribute to a preference for pricing controls.
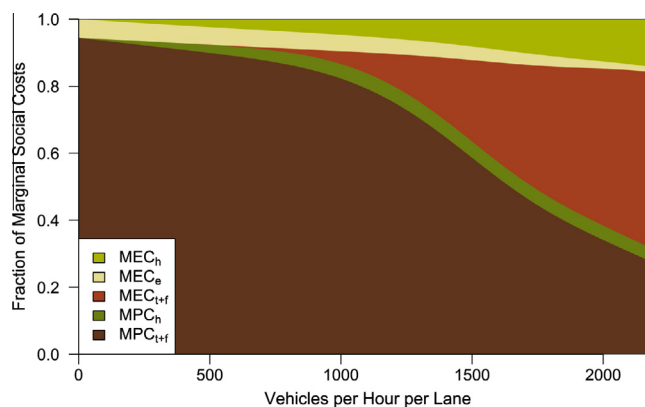

Fig. 2. Marginal cost components as share of total.

4.3. Equilibrium analysis

Using the observed average peak-period freeway traffic volume q = 1477 vphpl, a marginal benefit (MB) curve is generated at q by assuming $MB(q) = MPC_{t+f}(q)$. The MB curve is illustrated in Fig. 3 along with the same marginal cost curves as above. This allows determination of q^* (the optimal volume considering externalities), the Pigouvian Tax per vehicle mile of travel (MEC at q^*), and the welfare loss due to externalities (the area between the MSC and MB curves from q^* to q).

The optimal volume (q^*) is 1275 vphpl: 14% lower than observed q. The Pigouvian tax is $0.17/veh mile. For context, this tax equates to an additional $3.41/gallon, assuming a vehicle with 20 mile/gal fuel economy. The welfare loss due to externalities (i.e. $q \neq q^*$) is estimated at $36.13/h/ln mile, with a marginal external cost of MEC = $0.32/veh mile at q and an average external cost of $0.09/veh mile. If private health costs of exposure MPC_h is included in the tax to achieve q^*, then the tax increases by $0.04–$0.21/veh mile.[6] The effects of excluding the on-road pollution exposure cost components MEC_h and MPC_h would be a 4% higher estimated q^* (1326 vphpl), a 13% lower Pigouvian tax ($0.15/veh mile), and a residual welfare loss of $2.30/h/ln mile (6.4% of the un-taxed loss).

There is uncertainty in the private cost components that lead to the un-tolled equilibrium at q. As formulated in Eq. (6), MPC_{t+f} includes private time and fuel costs. Including private on-road exposure costs MPC_h or excluding private fuel costs MPC_f would shift the MB curve up or down, respectively, and change the value of q^* as well. At q, the time, fuel, and on-road exposure components of marginal private costs are MPC_t = $0.36, MPC_f = $0.18, and MPC_h = $0.04 per veh mile, respectively. With only private time costs considered at q, q^* = 1106 vphpl (13% lower) and the Pigouvian tax for all other marginal costs becomes $0.31/veh mile. With all MPC included at q (time, fuel, and on-road exposure), q^* = 1307 vphpl (3% higher) and the Pigouvian tax for MEC is $0.19/veh mile. Thus, the Pigouvian tax changes by only $0.02/veh mile depending on whether private on-road exposure costs are considered by travelers, but by $0.10/veh mile depending on whether private fuel costs are considered.

It is interesting to look at the expected marginal cost effects of a change in capacity on the study corridor. Using the same MB curve for Portland, a 10% increase in capacity q_c reduces private costs MPC at q by 3% and reduces external costs MEC by 32%. The new private equilibrium ($MB = MPC_{t+f}$) is at q = 1496 vphpl: a 1.3% increase. The new q^* from this equilibrium is 1310 vphpl, with a Pigouvian tax of $0.14/veh mile ($0.17/veh mile if including MPC_h). Considering the new q, q^*, and MSC curves, the new welfare loss in the system due to inefficient q is $25.22/h/ln mile (30% lower than $36.13/h/ln mile). At the higher equilibrium q the total social cost TSC decreases 1% ($11.31/h/ln mile), with a 15% decrease in total external costs and a 1% *increase* in total private costs. Total costs of time and on-road exposure decrease about 1%, while total fuel and pollution emissions costs are almost unchanged with the capacity expansion. The higher volume generates an increase in total social benefits TSB (Eq. (2).) of $10.73/h/ln mile, which, combined with the TSC reduction, is an increase in net benefits (social surplus) of $22.03/h/ln mile. Note that this is smaller than the welfare loss due to an inefficiently high q. Increasing capacity reduces the welfare loss from externalities and increases net social benefits, but it also increases the traffic volume, which offsets savings in emissions and fuel consumption rates.

4.4. Sensitivity analysis

To continue the hypothetical analysis, consider the unit cost ranges shown in Table 3. Varying the cost parameters ($c_t, c_f, c_{e,p}, c_{h,p}$) over the "Low Cost" to "High Cost" range leads to marginal external costs MEC at capacity q_c that vary from $0.86/veh mile to $3.87/veh mile (from the "Medium Cost" case of $2.06/veh mile). This is a wide range, indicative of the challenge of setting optimal road pricing to address congestion externalities. The largest source of this uncertainty stems from the time cost coefficient c_t; fixing this at its "Medium Cost" value and varying the other cost parameters, MEC at q_c only varies from $1.62/veh mile to $2.35/veh mile. The cost coefficients also impact the relative importance of the exposure cost components: combined private and external on-road exposure marginal costs ($MPC_h + MEC_h$) are 6% and 13% of marginal social costs at capacity when using the Low and High unit cost coefficients in Table 3, respectively.

Another source of uncertainty for health cost estimates is the dispersion and vehicle penetration parameters that are used to calculate K_p. Using Low, Medium, and High values of 0.0094, 0.0552, and 0.1480 for K_p (see Section 3), MEC at q_c is calculated as $1.71, $2.07, and $2.79 per veh mile. Similarly, the combined on-road exposure marginal costs ($MPC_h + MEC_h$) are 4%, 18%, and 38% of MSC at q_c using each value of K_p, respectively.

Demand elasticity is a parameter value known to vary in different contexts. While it does not affect marginal costs, the range of $-0.7 \leqslant \eta_q^\beta \leqslant -0.2$ in Table 3 impacts the shape of the MB curve and the equilibrium analysis results presented above. Less elastic demand (-0.2) leads to a 7% higher q^* (1368 vphpl), a 32% higher Pigouvian tax ($0.23/veh mile), and a 43% lower welfare loss at q ($20.43/h/ln mile). In contrast, more elastic demand (-0.7) leads to a 3% lower q^* (1231 vphpl), a 12% lower Pigouvian tax ($0.15/veh mile), and a 18% higher welfare loss at q ($42.52/h/ln mile).

To look at the extreme possibilities of the role of exposure costs, consider the case where all the unit costs except for health costs $c_{h,p}$ are at their "High" levels, and $c_{h,p}$ is at the "Low" level. In this situation on-road exposure marginal costs ($MPC_h + MEC_h$) are a mere 1.4% of marginal social costs at capacity q_c. If K_p is also set at its low value, ($MPC_h + MEC_h$) falls to 0.2% of MSC. Reversing this, if all other unit costs are at their "Low" levels and $c_{h,p}$ is at the "High" level, ($MPC_h + MEC_h$) are 37% of MSC at q_c. If K_p is then set at its high value instead of medium, ($MPC_h + MEC_h$) increases to 61% of MSC at q_c.

The set of parameters in the model is large and there is uncertainty represented by the wide ranges of parameter values in Table 3. The results in this section illustrate that the parameter value uncertainty translates into uncertainty about the rel-
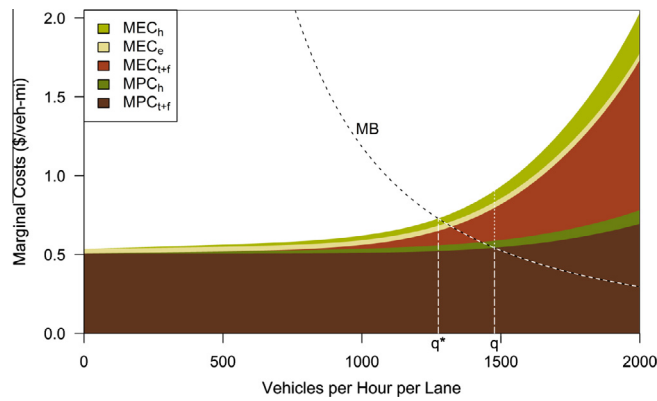
Fig. 3. Equilibrium analysis.

ative importance of on-road exposure costs. Some of this uncertainty is due to the variability of context-specific parameters, where the applicable range depends on the context. Setting all the unit cost and exposure parameters simultaneously to either their "Low Cost" or "High Cost" values in Table 3 represents the lowest and highest cost estimates, respectively.

In so far as the parameters are independent, a much smaller range of results would be expected. Correlation among parameter values would tend to widen the expected range of costs but the High values in Table 3 are a realistic worst-case scenario. For example, unit pollution cost estimates $c_{e,p}$ depend on the population density and atmospheric cleansing mechanisms in a city, because these determine the amount of human exposure that results from a given mass of pollution emissions. Because these factors are fairly consistent across pollutants we would expect correlation among some of the $c_{e,p}$ values in certain locations (higher in Los Angeles for example). The health unit costs of exposure $c_{h,p}$ could be similarly correlated if the traveling population in an area is of consistently good or poor health (and so less or more susceptible to the effects of pollution exposure). More research is needed not only to narrow the uncertainty in individual parameters, but to determine correlations among the parameters and the most likely combinations of parameter values for exposure cost estimates.

4.5. Policy implications

The welfare loss that could be eliminated with optimal pricing in the case study ($36.13/h/ln mile) can be annualized to $36,127/ln mile by assuming 4 congested peak hours per day and 250 congested days per year. To put this value into context, a recent report summarizing the costs and benefits of intelligent transportation system (ITS) implementations (ITS Joint Program Office, 2011) suggests $7.5 million per year for annualized capital, operations, and maintenance costs from integrated corridor management including lane pricing (using a sample 34-mile (250-lane mile) corridor). Using $36,127/ln mile, a corridor would have to be 208 lane miles to justify such an implementation through a change in social welfare. But this estimate is based on a case study corridor with a volume/capacity (q/q_c) ratio of only 0.7. For a roadway initially at 95% of capacity ($q/q_c = 0.95$), $q = 2090$ vphpl, $q^* = 1661$ vphpl, and the welfare loss that could be eliminated with first-best tolling is $327/h/ln mile. Annualizing by the same assumptions above, $7.5 million in welfare gains could be achieved on a corridor of only 23 lane miles. With the same assumptions but ignoring on-road exposure costs, $q^* = 1719$ vphpl, the welfare loss is $214/h/ln mile, and 35 lane miles are required to accrue the same annualized social welfare gains. In other words, including on-road exposure as an externality can reduce the size of corridor needed to justify an ITS congestion pricing system by 34%. Roadways with recurring congestion at near-capacity volumes can reasonably expect social welfare gains to exceed ITS pricing program implementation costs.

A similar comparison can be made between ITS benefits and costs for a traffic flow improvement such as ramp metering. The effect of ramp meters on a freeway with $q/q_c = 0.95$ can be estimated as a 5% increase in effective capacity leading to a 9% reduction in delay, from Schrank and Lomax (2009b). The social welfare gain from a 5% capacity increase (without tolling) is $66.63/h/ln mile including on-road exposure costs and $64.33/h/ln mile without on-road exposure costs. Thus, when on-road exposure costs are considered, the ITS deployment can be justified on a corridor with just 3% higher ramp density (ramps per lane mile) than when on-road exposure costs are ignored. However, in either case ramp metering is easily justified by social welfare gains assuming about $6000 annualized costs per ramp (ITS Joint Program Office, 2011). In summary, the inclusion of on-road exposure costs has a much smaller effect on estimates of net benefits from traffic flow improvements than on estimates of externality costs that can be addressed by pricing.

4.6. The role of heavy-duty vehicles

The impacts of heavy-duty or high-emitting vehicles is another policy consideration for on-road exposure costs. Previous research has shown that heavy-duty (HD) vehicles have a unique role in reducing emissions on congested freeways (Bigazzi and Figliozzi, 2013). Diesel–fueled HD vehicles are especially high emitters of $PM_{2.5}$ and NO_x and have emissions rates that

are more sensitive to congestion than light-duty vehicles' emissions rates. Additionally, HD vehicles exhibit disproportional roadway capacity utilization. We here compare the marginal external costs of HD vehicles to the *MEC* of the mixed vehicle fleet.

Assuming that HD vehicles use 50% more capacity than other vehicles (Transportation Research Board, 2000) and comprise 9% of the fleet, the marginal capacity used by each HD vehicle is 44% greater than the general mixed fleet of vehicles. This capacity adjustment affects the time, fuel, pollution, and on-road exposure external cost components. To adjust for distinct emissions characteristics affecting the pollution and exposure external costs MEC_e and MEC_h, average HD vehicle emissions rate parameters are drawn from the same emissions research used above (Bigazzi and Figliozzi, 2013). The estimated HD vehicle emissions rates at q_c are 3.3, 1.6, 9.4, 7.3, and 4.4 times greater than the mixed fleet average emissions rates for CO_2e, CO, $PM_{2.5}$, NO_x, and HC, respectively.

With these capacity and emissions rate adjustments, marginal external costs *MEC* are 85% higher at q_c for HD vehicles than for the mixed fleet, with the greatest differences attributable to the pollution and exposure externalities. The *MEC* difference is even larger in free-flow (low-volume) conditions, where *MEC* for HD vehicles is more than 5 times that of the general fleet (because of higher emissions rates). At low q without congestion costs, *MEC* for HD vehicles is around $0.15/veh mile, roughly on par with current per-mile charges for heavy trucks in Oregon[7] (which are based entirely on infrastructure costs). The time and fuel external cost components MEC_t and MEC_f are 44% greater for HD vehicles at all q because of the capacity adjustment.

At low volumes the exposure externality MEC_h is 6.5 times greater for HD vehicles and the pollution externality MEC_e is 5.2 times greater. At volumes near capacity MEC_h is 3.0 times greater for HD vehicles and MEC_e is 4.8 times greater. The differences are smaller at higher q because the effects of the capacity adjustment (which are smaller than the emissions rate effects) become more important in congestion. This is especially true for the exposure externality MEC_h, which is increasingly caused by delay to other vehicles for volumes near capacity. The impact of considering the on-road exposure externality is more important for HD vehicle marginal costs than for the general fleet: including on-road exposure increases marginal external costs at capacity by 27% for the mixed fleet, but increases *MEC* at q_c by 53% for HD vehicles. In agreement with our marginal pollution externality estimates MEC_e, a recent multi-class tolling study found optimal environmental tolls (excluding greenhouse gases) to be 3–4 times higher for large trucks than passenger cars, dominated by NO_x costs (Holguín-Veras and Cetin, 2009).

This analysis considered only a general heavy-duty vehicle class. A smaller subset of extremely high-emitting vehicles with greater emissions rates would further increase the marginal external costs for these vehicles – both in and out of congestion. This is a potentially important distinction, as very high on-road pollution exposures have been linked to a small set of high-emitting vehicles (Bigazzi and Figliozzi, 2012b). In addition to the marginal cost differences, marginal benefits are expected to vary by vehicle class, and could have private and external components (especially for HD vehicles, which are mostly freight). A full analysis of how to address the distinct emissions and exposure costs of heavy-duty and high-emitting vehicles with pricing mechanisms is left as a topic for future study. Although these topics have been explored in the past (Holguín-Veras and Cetin, 2009), the results in this paper show that on-road exposure costs is an externality that warrants inclusion.

5. Conclusions

The health cost of on-road air pollution exposure is a component of traffic marginal costs that has not previously been assessed. As a main objective, this paper develops marginal private and external cost equations that include on-road pollution exposure in addition to time, fuel, and pollution emissions components. The expression for marginal external costs 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.

Using a range of parameter values based on the literature, this paper demonstrates that health costs of on-road pollution exposure can be a large portion (18%) of marginal social costs near freeway capacity. In a first-best pricing scenario, excluding the on-road exposure externality can lead to 6% residual welfare losses because of under-calculated tolls. Time is the dominant cost component, but health costs increase dramatically in congestion. While regional pollution generates greater costs in uncongested conditions, on-road exposure comes to dominate health costs on congested freeways because of the increased duration and intensity of exposure.

The optimal tolls, external costs, and volume changes after pricing estimated in a case study of freeways in Portland, Oregon are within range of the literature (HDR, 2009; Proost et al., 2002). Still, there are large uncertainties in the estimates due to uncertain parameter values, as illustrated in Section 4.4. With different exposure parameters the marginal health costs of on-road exposure at capacity can be as little as 4% or as much as 38% of all marginal costs. Unit cost parameters also strongly influence the relative importance of on-road exposure costs. The estimation of health outcomes due to varying intensity and duration of exposure during travel is particularly challenging.

The estimated marginal cost and benefit curves indicate a theoretical preference for price controls to address the externality problem. Increasing roadway capacity is one way to reduce external costs of congestion – but it also increases traffic

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[7] http://www.hotshotcarrier.com/DOToregonhutguide.pdf.

volume and total private costs, without reducing environmental externalities (pollution emissions). At volumes near capacity, corridor pricing and traffic flow improvements through ramp metering are both reasonably justified by net social welfare gains. The inclusion of on-road exposure costs affects the estimation of cost savings from ITS improvements – with a much larger benefit for pricing systems than traffic flow improvements. The sizes of projects required to cover implementation costs decrease when on-road exposure costs are considered: pricing is justified on a 34% smaller corridor, and ramp metering is justified with 3% fewer lane miles per ramp. When considering distinct vehicle classes, inclusion of on-road exposure costs disproportionately affects heavy-duty vehicle marginal costs because of higher emissions rates and greater roadway capacity utilization. While marginal external costs at capacity for the general fleet increase by 27% when on-road exposure is included, for heavy-duty vehicles the increase is twice as large (53%).

Vehicle emissions rates will change over time as the vehicle fleet evolves with new engine technology and fuels (electric and hybrid vehicles, biofuels, etc.). A scalar reduction in emissions rates $e_p(q)$ will decrease the external costs of congestion. If advanced vehicles are also less sensitive to congestion, then external costs will be further reduced because of lower emissions rate sensitivity $e'_p(q)$ (Bigazzi and Figliozzi, 2012a). These effects would reduce the importance of both on-road and regional pollution costs of congestion. On-road exposure costs will also be reduced as newer vehicles have better-sealed vehicle cabins, reducing the pollutant penetration parameter P_p (Fruin et al., 2011). However, a switch to biofuels may bring about increases in emissions rates for some pollutants such as NO_x and certain organic compounds (He et al., 2009; Ropkins et al., 2007). Particulate emissions due to brake and tire wear and traffic-induced particulate resuspension will likely be undiminished with an advanced fleet, though this will depend on the level of regenerative braking and the future composition and durability of vehicle tires. These considerations could be studied by interfacing the present study with vehicle fleet projection models.

This paper is a first demonstration of incorporating on-road pollution exposure externalities into economic analysis of freeway traffic. More research is needed on parameter values for the exposure cost equations – especially exposure unit costs (which require new linkages between short-duration repeated exposure and health outcomes) and dispersion parameters (which require better on-road exposure modeling tools). For emissions such as NO_x, consideration should be given to the interaction with secondary pollutants such as ozone and the possibility for separation into constituents (i.e. NO and NO_2). Another issue is the proper classification of on-road exposure costs as private or external: are they perceived by travelers and reflected in travel behavior? The modeled congestion costs could be extended to include exposure for other travelers on the corridor (counter-flowing traffic, pedestrians) and near-road exposure for non-travelers. This would provide more detail than the present on-road/regional exposure split, and allow assessment of environmental justice issues in certain contexts. Finally, further consideration should be given to the emissions-related congestion costs of distinct vehicle classes and high-emitting vehicles – including analysis of vehicle class-segregated facilities and class-specific pricing.

Acknowledgments

References

Bickel, P., Friedrich, R., Link, H., Stewart, L., Nash, C., 2006. Introducing environmental externalities into transport pricing: measurement and implications. Transport Reviews 26, 389–415.

Bigazzi, A.Y., Figliozzi, M.A., 2011. Freeway traffic flow optimization considering delay, emissions, and fuel costs with stochastic capacity, In: 52nd Annual Transportation Research Forum. Long Beach, CA.

Bigazzi, A.Y., Figliozzi, M.A., 2012a. Congestion and emissions mitigation: a comparison of capacity, demand, and vehicle based strategies. Transportation Research Part D: Transport and Environment 17, 538–547.

Bigazzi, A.Y., Figliozzi, M.A., 2012b. Impacts of freeway traffic conditions on in-vehicle exposure to ultrafine particulate matter. Atmospheric Environment 60, 495–503.

Bigazzi, A.Y., Figliozzi, M.A., 2013. Role of heavy-duty freight vehicles in reducing emissions on congested freeways with elastic travel demand functions. Transportation Research Record: Journal of the Transportation Research Board 2340, 84–94.

Bigazzi, A.Y., Figliozzi, M.A., Clifton, K.J., Traffic Congestion and Air Pollution Exposure for Motorists: Comparing Exposure Duration and Intensity, International Journal of Sustainable Transportation, 2013 (Forthcoming).

Bilbao-Ubillos, J., 2008. The costs of urban congestion: estimation of welfare losses arising from congestion on cross-town link roads. Transportation Research Part A: Policy and Practice 42, 1098–1108.

Brilon, W., Geistefeldt, J., Zurlinden, H., 2007. Implementing the concept of reliability for highway capacity analysis. Transportation Research Record: Journal of the Transportation Research Board 2027, 1–8.

Brunekreef, B., Beelen, R.M.J., Hoek, G., Schouten, L.J., Bausch-Goldbohm, S., Fischer, P., Armstrong, B., Hughes, E., Jerrett, M., van den Brandt, P.A., 2009. Effects of long-term exposure to traffic-related air pollution on respiratory and cardiovascular mortality in the Netherlands? The NLCS-AIR study. Health Effects Institute Research Reports, 1–94.

Bureau of Public Roads, 1964. Traffic Assignment Manual. US Department of Commerce.

Burnett, R.T., Cakmak, S., Raizenne, M.E., Stieb, D., Vincent, R., Krewski, D., Brook, J.R., Philips, O., Ozkaynak, H., 1998. The association between ambient carbon monoxide levels and daily mortality in Toronto, Canada. Journal of the Air & Waste Management Association 48, 689–700.

De Borger, B., Wouters, S., 1998. Transport externalities and optimal pricing and supply decisions in urban transportation: a simulation analysis for Belgium. Regional Science and Urban Economics 28, 163–197.

Delucchi, M.A., 2000. Environmental externalities of motor-vehicle use in the US. Journal of Transport Economics and Policy 34, 135–168.

Delucchi, M.A., McCubbin, D.R., 2010. External Costs of Transport in the US. In: Handbook of Transport Economics. Edward Elgar Publishing Ltd..

Federal Highway Administration, 2005. Highway Economic Requirements System – State Version. US Department of Transportation.
Fruin, S.A., Hudda, N., Sioutas, C., Delfino, R.J., 2011. Predictive model for vehicle air exchange rates based on a large, representative sample. Environmental Science and Technology 45, 3569–3575.
Fruin, S.A., Westerdahl, D., Sax, T., Sioutas, C., Fine, P.M., 2008. Measurements and predictors of on-road ultrafine particle concentrations and associated pollutants in Los Angeles. Atmospheric Environment 42, 207–219.
Goodwin, P., Dargay, J., Hanly, M., 2004. Elasticities of road traffic and fuel consumption with respect to price and income: a review. Transport Reviews 24, 275–292.
Grabow, M.L., Spak, S.N., Holloway, T., Stone, B., Mednick, A.C., Patz, J.A., 2012. Air quality and exercise-related health benefits from reduced car travel in the midwestern united states. Environ Health Perspect 120, 68–76.
HDR, 2008. Freight Benefit/Cost Study: Highway Freight Logistics Reorganization Benefits Estimation Tool Report and Documentation (No. FHWA-HOP-08-017). Federal Highway Administration, Washington, DC
HDR, 2009. Assessing the Full Costs of Congestion on Surface Transportation Systems and Reducing Them through Pricing. US Department of Transportation, Washington, DC
He, C., Ge, Y., Tan, J., You, K., Han, X., Wang, J., You, Q., Shah, A.N., 2009. Comparison of carbonyl compounds emissions from diesel engine fueled with biodiesel and diesel. Atmospheric Environment 43, 3657–3661.
Health Effects Institute, 2010. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects (Special Report No. Special Report 17). Health Effects Institute.
Holguín-Veras, J., Cetin, M., 2009. Optimal tolls for multi-class traffic: analytical formulations and policy implications. Transportation Research Part A: Policy and Practice 43, 445–467.
Horowitz, A.J., 1991. Delay/Volume Relations for Travel Forecasting Based upon the 1985 Highway Capacity Manual. Federal Highway Administration, Washington, DC.
Hudda, N., Kostenidou, E., Sioutas, C., Delfino, R.J., Fruin, S.A., 2011. Vehicle and driving characteristics that influence in-cabin particle number concentrations. Environmental Science & Technology 45, 8691–8697.
ITS Joint Program Office, 2011. Intelligent Transportation Systems Benefits, Costs, Deployment, and Lessons Learned Desk Reference: 2011 Update (No. FHWA-JPO-11-140). Federal Highway Administration, Washington, DC.
Johan de Hartog, J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ Health Perspect 118, 1109–1116.
Johansson, O., 1997. Optimal road-pricing: simultaneous treatment of time losses, increased fuel consumption, and emissions. Transportation Research Part D: Transport and Environment 2, 77–87.
Kaur, S., Nieuwenhuijsen, M.J., Colvile, R.N., 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmospheric Environment 41, 4781–4810.
Lemp, J.D., Kockelman, K.M., 2008. Quantifying the external costs of vehicle use: evidence from America's top-selling light-duty models. Transportation Research Part D: Transport and Environment 13, 491–504.
Litman, T., 2009. Transportation Cost and Benefit Analysis: Techniques, Estimates and Implications. Victoria Transport Policy Institute, Victoria, Canada.
Macharis, C., Van Hoeck, E., Pekin, E., Van Lier, T., 2010. A decision analysis framework for intermodal transport: comparing fuel price increases and the internalisation of external costs. Transportation Research Part A: Policy and Practice 44, 550–561.
Maibach, M., Schreyer, C., Sutter, D., Van Essen, H.P., Boon, B.H., Smokers, R., Schroten, A., Doll, C., Pawlowska, B., Bak, M., 2007. Handbook on estimation of external cost in the transport sector (No. 07.4288.52). CE Delft, The Netherlands.
Mayeres, I., Ochelen, S., Proost, S., 1996. The marginal external costs of urban transport. Transportation Research Part D: Transport and Environment 1, 111–130.
McCubbin, D.R., Delucchi, M.A., 1999. The health costs of motor-vehicle-related air pollution. Journal of Transport Economics and Policy 33, 253–286.
Muller, N.Z., Mendelsohn, R., 2007. Measuring the damages of air pollution in the United States. Journal of Environmental Economics and Management 54, 1–14.
Nafstad, P., Håheim, L.L., Wisløff, T., Gram, F., Oftedal, B., Holme, I., Hjermann, I., Leren, P., 2004. Urban air pollution and mortality in a cohort of Norwegian men. Environ Health Perspect 112, 610–615.
National Research Council, 2010. Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. National Academies Press, Washington, DC.
Noland, R.B., Lem, L.L., 2002. A review of the evidence for induced travel and changes in transportation and environmental policy in the US and the UK. Transportation Research Part D: Transport and Environment 7, 1–26.
Ozbay, K., Bartin, B., Yanmaz-Tuzel, O., Berechman, J., 2007. Alternative methods for estimating full marginal costs of highway transportation. Transportation Research Part A: Policy and Practice 41, 768–786.
Parry, I.W.H., Walls, M., Harrington, W., 2007. Automobile Externalities and Policies (RFF Discussion Paper No. 06-26). Social Science Research Network.
Pope, C.A.I., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287, 1132–1141.
Pope, C.A.I., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. Journal of the Air & Waste Management Association 56, 709–742.
Proost, S., Dender, K.V., 2008. Optimal urban transport pricing in the presence of congestion, economies of density and costly public funds. Transportation Research Part A: Policy and Practice 42, 1220–1230.
Proost, S., Dender, K.V., Courcelle, C., De Borger, B., Peirson, J., Sharp, D., Vickerman, R., Gibbons, E., O'Mahony, M., Heaney, Q., Van den Bergh, J., Verhoef, E., 2002. How large is the gap between present and efficient transport prices in Europe? Transport Policy 9, 41–57.
Ropkins, K., Quinn, R., Beebe, J., Li, H., Daham, B., Tate, J., Bell, M., Andrews, G., 2007. Real-world comparison of probe vehicle emissions and fuel consumption using diesel and 5% biodiesel (B5) blend. Science of the Total Environment 376, 267–284.
Santos, G., Behrendt, H., Maconi, L., Shirvani, T., Teytelboym, A., 2010. Part I: externalities and economic policies in road transport. Research in Transportation Economics 28, 2–45.
Schrank, D., Lomax, T., 2009a. The 2009 Urban Mobility Report. Texas Transportation Institute, College Station, TX.
Schrank, D., Lomax, T., 2009b. Six Congestion Reduction Strategies and Their Effects on Mobility. Texas Transportation Institute, College Station, TX.
Shepherd, S.P., 2008. The effect of complex models of externalities on estimated optimal tolls. Transportation 35, 559–577.
Small, K.A., Kazimi, C., 1995. On the costs of air pollution from motor vehicles. Journal of Transport Economics and Policy 29, 7–32.
Small, K.A., Verhoef, E., 2007. The Economics of Urban Transportation. 2nd ed. Routledge.
Transportation Research Board, 2000. Highway Capacity Manual. National Research Council, Washington, DC.
US Environmental Protection Agency, 2005. Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel (No. EPA420-F-05-001), Emission Facts. Washington, DC.
US Environmental Protection Agency, 2009. Motor Vehicle Emission Simulator (MOVES) 2010 User's Guide (No. EPA-420-B-09-041). Washington, DC.
Walters, A.A., 1961. The theory and measurement of private and social cost of highway congestion. Econometrica 29, 676–699.
Weitzman, M.L., 1974. Prices vs. quantities. The Review of Economic Studies 41, 477–491.
Xu, B., Zhu, Y., 2009. Quantitative analysis of the parameters affecting in-cabin to on-roadway (I/O) ultrafine particle concentration ratios. Aerosol Science and Technology 43, 400–410.