Marginal Costs of Freeway Traffic Congestion with On-Road Pollution Exposure Externality

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Submitted to the 92nd Annual Meeting of the Transportation Research Board
January, 2013
(Revised: November, 2012)

7,416 Words [6,416 + 3 figure x 250 + 1 table x 250]
ABSTRACT

The health cost of on-road air pollution exposure is a component of marginal costs in congested traffic that has not previously been assessed. The main objective of this paper is to introduce on-road pollution exposure as an externality of traffic congestion. Marginal private and external cost equations are developed that include on-road pollution exposure in addition to time, fuel, and regional pollution emissions components. Applying a set of parameter values based on the literature shows that on-road pollution exposure can be a large portion (18%) of marginal costs near freeway capacity. In an optimal pricing scenario, excluding the on-road exposure externality can lead to 6% residual welfare losses because of sub-optimal tolls. Time is the dominant cost component, but on-road exposure costs increase dramatically in congestion. 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 reduces the sizes of projects required to cover implementation costs for intelligent transportation system improvements, with more of an effect on the estimated benefits of road-pricing systems than traffic flow improvements. 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 occupation of roadway capacity. Lastly, there are large uncertainties in the parameter estimates and more research is needed for on-road exposure modeling tools and linkages between repeated short-duration pollution exposure and health outcomes.

1 INTRODUCTION

The total costs of traffic congestion are large, with estimates in the hundreds of billions of dollars annually for the U.S. [1]. 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 [2–4]. Capacity-based congestion management tools to reduce the costs of traffic congestion 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 quantity controls (such as freeway ramp meters or travel day restrictions) or price controls (such as congestion/roadway charges or tolls).

Economic assessments of externalities from road travel include costs of air pollution emissions, noise, space consumption, fuel consumption, vehicle maintenance, road maintenance, and other dimensions [4–12]. The external costs due to traffic congestion are sometimes calculated as the increased time costs alone [10], [12–14], though estimates of marginal congestion costs have included other externalities, often in the context of roadway pricing systems [15–17].

What has not been considered as a component of marginal congestion costs is the human health impact of in-vehicle pollution exposure for travelers. In-vehicle pollution exposure, because of the high concentrations found on roadways, can be a significant portion of people’s daily exposure [18]. The health costs of exposure to vehicle emissions for a regional population have previously been quantified as an externality, but on-road exposure is distinct because it is a function of travel duration in addition to the quantity of vehicle emissions. Each additional vehicle can increase other travelers’ on-road exposure costs (in addition to time costs) by increasing their travel time.

The main objective of this paper is to introduce on-road 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 (a large-sized U.S. city). The issue of
theoretical preference for price versus quantity controls to achieve optimal traffic volumes is considered.

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 of analysis time as the output measure.

2.1 Social Costs & Benefits in Traffic

The total social cost (TSC) of freeway travel considered here is comprised of the 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). Expressed as a function of the travel demand volume $q$ (in vehicles per hour per lane, or vphpl), $TSC$ is

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

in $\text{\$ per hour of analysis time}$, 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), $l_p(q)$ 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 $\text{\$ per vehicle-hour, \$ per gallon, \$ per kg, and \$ per person-hour-mg/m}^3$. Pollution emissions 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 $\text{\$ per hour of analysis time}$

$$TSB(q) = l \int_0^q \beta(q) \, dq,$$

where $\beta(q)$ is the marginal benefit of travel in $\text{\$ per vehicle-mile}$. The marginal social costs (MSC) are found by differentiating Equation 1:

$$MSC(q) = \frac{\partial TSC(q)}{\partial q} = l \left\{ c_t [t'(q) + q t''(q)] + c_f [f'(q) + q f''(q)] + \sum_p [c_{e,p} e_p'(q) + q c_{e,p} e_p''(q)] + \sum_p [c_{h,p} l_p'(q) + q c_{h,p} l_p''(q)] \right\}$$

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

1 In reduced form the marginal cost units are $\frac{\text{\$ lane}}{\text{vehicle}}$, though perhaps more intuitively they are in $\text{\$ per vehicle/lane}$.
\[ MPC(q) = l \left[ c_t t(q) + c_f f(q) + \sum_p \left( c_{h_p} I_p(q) \right) \right] \]  

includes the marginal travelers’ time, fuel, and on-road exposure costs, and

\[ MEC(q) = l \left[ c_t q t'(q) + c_f q f'(q) + \sum_p \left( c_{e_p} e_p(q) + q c_{e_p} e_p'(q) + q c_{h_p} I_p'(q) \right) \right] \]  
is all other social costs. Further subdividing, direct \( MPC \) are the marginal traveler’s perceived costs, assumed to be the time and fuel components [12]:

\[ MPC_{direct}(q) = l \left[ c_t t(q) + c_f f(q) \right] \]  
and indirect \( MPC \) (health costs from on-road pollution exposure) are

\[ MPC_{indirect}(q) = l \sum_p \left[ c_{h_p} I_p(q) \right] \]  

This distinction is made with the consideration that although exposure costs for the marginal traveler are internal, it is likely that the marginal traveler is not accounting for them in travel decision-making. Thus, private equilibrium will be expected based on \( MPC_{direct} \), not \( MPC \).

The marginal benefits at \( q \) are

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

\[ \eta^\beta_q = \frac{\beta(q)}{q} \frac{\partial q}{\partial \beta(q)} \]  
estimable from the economic literature\(^2\). From Equation 9,

\[ \beta(q) = \gamma \cdot \exp \left( \frac{\ln q}{\eta^\beta_q} \right) \]  
where \( \gamma \) is a constant. By assuming an observed equilibrium volume at \( MB(q) = MPC_{direct}(q) \), the MB curve can be drawn from an estimate of \( \gamma \) as

\[ \gamma = \frac{MPC_{direct}(q)}{l} \exp \left( -\frac{\ln q}{\eta^\beta_q} \right) \]  
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 MEC at \( q^* \) – the Pigouvian toll [3].

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 \[ q \cdot n \cdot e_p(q) \cdot \frac{P_p}{D_p} \], 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

\[
I_p(q) = O \cdot t(q) \cdot q \cdot n \cdot e_p(q) \cdot \frac{P_p}{D_p}, \tag{12}
\]

where \( O \) is the average vehicle occupancy (persons/vehicle). Assuming \( P_p \) and \( D_p \) are fixed parameters with respect to \( q \), if \( D_p \) is in units of \( m^2/\text{sec} \) then Equation 12 simplifies with a new parameter \( K_p \), where

\[
K_p = \frac{nO P_p}{D_p} \left[ \frac{1 \text{mi}}{1.609 \text{m}} \cdot \frac{10^6 \text{mg}}{\text{kg}} \cdot \frac{1 \text{hr}}{3,600 \text{sec}} \right] \tag{13}
\]

in \( \frac{\ln\text{person-hr-\text{mi}}}{\text{veh-m}^2\text{kg}} \). Then,

\[
I_p(q) = K_p \cdot q \cdot t(q) \cdot e_p(q) \tag{14}
\]

in person-hr-mg/m\(^3\) per veh-mi. 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. Differentiating Equation 14,

\[
I_p'(q) = K_p \left\{ q \cdot t(q) \cdot e_p'(q) + q \cdot t'(q) \cdot e_p(q) + t(q) \cdot e_p'(q) \right\}. \tag{15}
\]

Equations 14 and 15 can be substituted into the preceding marginal cost equations containing \( I_p(q) \) or \( I_p'(q) \). Thus, the on-road exposure health costs are

\[
MPC_{\text{health}}(q) = \ell qt(q) \sum_p [c_{np} K_p e_p(q)] \quad \text{and} \quad MEC_{\text{health}}(q) = \ell q \sum_p [c_{np} K_p (qt(q) e_p'(q) + qt'(q) e_p(q) + t(q) e_p(q))]. \tag{16, 17}
\]

The three terms in brackets in Equation 17 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 vehicles caused by additional congestion from the marginal vehicle, and 3) the marginal vehicle’s own emissions.

2.3 Functional Forms

The functional form used for \( t(q) \) is the well-known Bureau of Public Roads (BPR) function [3], [21]. This is a static, time-averaged model of roadway performance with parameters of \( a \) and \( b \) (unitless), the free-flow travel rate \( t_o \) (hr/mi) and volume capacity \( q_c \) (vph/1):\(^3\)

\[
t(q) = t_o \left( 1 + a \left( \frac{q}{q_c} \right)^b \right). \tag{18}
\]

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

\(^3\) We do not adjust for passenger-car equivalency, assuming \( \frac{q}{q_c} \) is unaffected by units of vehicles or “passenger car equivalents”.

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Emissions rates for pollutant \( p \) are drawn from previous emissions research \[22\] using the form

\[ e_p(q) = \exp\left(\sum_{i=0}^{4} a_{i,p} t(q)^{-i}\right), \quad (19) \]

which makes use of \( t(q) \) in Equation 18. 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\(_2\)e per gallon of fuel \[23\], \( f(q) \) in gallons per vehicle-mile is

\[ f(q) = e_{CO_2e}(q)/10, \quad (20) \]

and \( f'(q) = e'_{CO_2e}(q)/10 \).

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 \[24\], the “comparative advantage” of price over quantity controls, assuming independently distributed costs and benefits, is assessed by the parameter

\[ \Delta = \frac{\sigma^2(MB' + MSC')}{2 \cdot MSC'^2}, \quad (21) \]

where \( \sigma^2 \) is the expected variance (mean square error) in MSC and \( MB' \) and \( MSC' \) are differentiated with respect to \( q \); i.e., \( MB' = \frac{\partial MB}{\partial q} = l \beta'(q) = \frac{\nu}{\eta q} \exp\left(\frac{\ln q}{\eta q}\right) \). A positive \( \Delta \) favors a price control (e.g., tax or toll), while a negative \( \Delta \) favors quantity control (e.g., traffic control measures). Conveniently, the sign of \( \Delta \) is simply the sign of \( MB' + MSC' \) (which does not require estimation of \( \sigma^2 \)). The magnitude of the comparative advantage increases with \( \sigma^2 \). Using a stochastic model of traffic flow breakdown where there is a greater likelihood of queue formation near roadway capacity \[25\], we expect \( \sigma^2 \) to increase as \( q \) approaches \( q_c \) because of the uncertainty of costs \[26\].

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-mi) of roadway. Selected parameter and unit cost estimates are shown in Table 1. “Medium” parameter values are assumed initially, and the low/high range is tested below for sensitivity analysis. All prices are in 2011 US$, adjusted using the annual average urban Consumer Price Index from the U.S. Bureau of Labor Statistics\[4\]. Unit time costs \( (\epsilon_t) \) are estimated for a volume-weighted average vehicle, including business travel and freight.

\[ ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt \]
Table 1 Case Study Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Units</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_q^\beta )</td>
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<td>-0.5</td>
<td>-0.7</td>
<td>-</td>
<td>[3], [6], [19], [20]</td>
</tr>
<tr>
<td>( D_p )</td>
<td>7</td>
<td>9</td>
<td>11</td>
<td>m²/s</td>
<td>[27]</td>
</tr>
<tr>
<td>( P_p )</td>
<td>0.2</td>
<td>0.8</td>
<td>1.0</td>
<td>-</td>
<td>[28], [29]</td>
</tr>
<tr>
<td>( O )</td>
<td>1</td>
<td>1.2</td>
<td>2</td>
<td>persons/veh</td>
<td>[30]</td>
</tr>
<tr>
<td>( c_t )</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>$/veh-hr</td>
<td>[17], [30], [31]</td>
</tr>
<tr>
<td>( c_f )</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>$/gal</td>
<td>Assumed</td>
</tr>
<tr>
<td>( c_{e,CO_2e} )</td>
<td>0.01</td>
<td>0.023</td>
<td>0.07</td>
<td>$/kg</td>
<td>[5], [17], [32]</td>
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<tr>
<td>( c_{e,CO} )</td>
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<td>0.37</td>
<td>0.60</td>
<td>$/kg</td>
<td>[17], [30]</td>
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<tr>
<td>( c_{e,PM_{2.5}} )</td>
<td>6.26</td>
<td>75.76</td>
<td>372.19</td>
<td>$/kg</td>
<td>[5], [30], [33], [34]</td>
</tr>
<tr>
<td>( c_{e,NO_x} )</td>
<td>2.94</td>
<td>14.54</td>
<td>40.38</td>
<td>$/kg</td>
<td>[5], [12], [17], [30], [34], [35]</td>
</tr>
<tr>
<td>( c_{e,HC} )</td>
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<td>12.91</td>
<td>19.86</td>
<td>$/kg</td>
<td>[17], [30], [34], [35]</td>
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<tr>
<td>( c_{h,CO_2e} )</td>
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<td>0</td>
<td>0</td>
<td>$/person-hr-mg/m³</td>
<td>Assumed</td>
</tr>
<tr>
<td>( c_{h,CO} )</td>
<td>0.05</td>
<td>0.14</td>
<td>0.33</td>
<td>$/person-hr-mg/m³</td>
<td>[36]</td>
</tr>
<tr>
<td>( c_{h,PM_{2.5}} )</td>
<td>3.29</td>
<td>16.46</td>
<td>32.92</td>
<td>$/person-hr-mg/m³</td>
<td>[37–39]</td>
</tr>
<tr>
<td>( c_{h,NO_x} )</td>
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<td>26.34</td>
<td>32.92</td>
<td>$/person-hr-mg/m³</td>
<td>[39], [40]</td>
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<tr>
<td>( c_{h,HC} )</td>
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<td>0</td>
<td>0</td>
<td>$/person-hr-mg/m³</td>
<td>Could not be determined</td>
</tr>
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</table>

Emissions and health unit costs are for five pollutants, \( p \): greenhouse gases (CO₂e), carbon monoxide (CO), fine particulates (PM₂.₅), nitrogen oxides (NOₓ), and hydrocarbons (HC). The emissions costs (\( c_e \)) 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 estimates). Literature on VOC (volatile organic compound) emissions cost estimates are applied for \( c_{e,HC} \) because of availability.

Unit cost estimates for on-road pollution exposure (\( c_h \)) are less readily available than \( c_e \). Greenhouse gases (CO₂e) are assumed to have no health impact through on-road exposure. Other pollutant costs are estimated based on a relative risk of mortality from long-term 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 U.S. annual all-cause working-age mortality rate of 0.39%, following [41]. The values of \( c_h \) in Table 1 are then computed by using estimates from the epidemiology literature of changes in relative risk of all-cause mortality with changes in exposure concentration.

The “Medium” value estimates of \( c_h \) in Table 1 use mortality risk increases of 4.2% per mg/m³ increase in CO exposure concentration [36], 0.6% per μg/m³ increase in PM₂.₅ [37], and 0.8% per μg/m³ increase in NOₓ [40]. The value ranges in Table 1 come from the same literature, as well as [39]. A lack of applicable studies prevents similar \( c_h \) 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 impacts from aggregate population exposure [42]. 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 [37].

The parameters necessary for estimating $K_p$ are $D_p$, $P_p$, and $O$ (Equation 13); using the values in Table 1, the low, medium, and high estimates of $K_p$ are 0.0094, 0.0552, and 0.1480 in $\frac{\text{ln-person-hr-mi}}{\text{mg \ veh-m^3-kg}}$.

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 $a = 0.83$, $b = 5.5$, $t_o = 1/60$, and $q_c = 2,200$ [43]. Emissions parameter estimates ($a_{i,p}$) for Equation 19 are from Bigazzi and Figliozzi [22], who generated emissions rates using the MOVES motor vehicle emissions model [44] with a 2010 vehicle fleet from Portland, Oregon composed of 9% heavy-duty vehicles.

4 RESULTS

For $q$ up to 2,200 vphpl ($q_c$), the modeled average speed falls from 60 mph to 33 mph. The modeled average fuel efficiency falls from 23 to 20 mpg. Emissions rates are 10% to 61% higher at $q = q_c$ than in free-flow conditions, with the greatest percent increases for PM$_{2.5}$ and HC emissions. On-road exposure concentrations at $q = q_c$ 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$_{2.5}$ [45], 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 are shown in Figure 1 for $q$ from 0 to 2,200 vphpl. The costs are shown cumulatively as stacked areas, with marginal costs in $/hr per ln-mi for each additional vphpl, or simply $/veh-mi on the corridor. At low $q$ the costs are predominantly $MPC_{direct}$ (time and fuel), with a small MEC from pollution emissions of $0.03$/veh-mi. Low-volume $MSC$ around $0.50$/veh-mi increase dramatically to $3$/veh-mi at $q_c$. All cost components increase in congestion, but the largest increase is for $MEC$ (which is dominated by time costs.). Because $MEC$ is also the Pigouvian tax, first-best congestion charges in Figure 1 range from $0$ to over $2$/veh-mi.
Figure 1 Marginal Costs

Figure 2 shows the marginal costs further separated and normalized to the total MSC: each shaded area is the fraction of MSC from each cost component. MPC decrease from 94% of MSC to only 31% at \( q_c \). 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 (Equation 17). All marginal cost components increase in congestion, but less so than \( MEC \) of exposure and time; the \( MEC \) of pollution 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, \( \mathrm{CO}_2 \) and \( \mathrm{NO}_x \) dominate the pollution \( MEC \) with 33% and 42% of the costs, respectively, at high \( q_c \). The shares change slightly with \( q \) because HC and PM_{2.5} are more sensitive to congestion than the other pollutants. \( \mathrm{NO}_x \) also dominates the exposure \( MEC \) at \( q_c \) the estimated \( MEC \) due to CO, PM_{2.5}, and \( \mathrm{NO}_x \) exposure are \$0.006, \$0.012, and \$0.42 per veh-mi, respectively. In contrast, at \( q_c \) the pollution \( MEC \) is \$0.05/veh-mi and time and fuel \( MEC \) are \$1.52/veh-mi and \$0.06/veh-mi, respectively. At \( q_c \) private costs are \( MPC_{direct} = \$0.81/veh-mi \) and \( MPC_{indirect} = \$0.12/veh-mi \). The exposure components of \( MPC \) and \( MEC \) are 4% and 14%, respectively, of \( MSC \) at \( q_c \), showing the potential importance of considering the on-road exposure externality.

Estimated average (not marginal) pollution costs are around \$0.03/veh-mi, and the average externality cost per vehicle-mile at \( q_c \) is \$0.37/veh-mi; both are within a reasonable range as reported in the externality literature [6], [8], [9]. The dominance of \( \mathrm{NO}_x \) in the pollution externality estimates (per vehicle-mile) is consistent with some of the literature [7], [35], but others have found PM_{2.5} costs per vehicle-mile to be higher than \( \mathrm{NO}_x \) costs [33], [46]. Some differences in cost estimates depend on how ambient pollution effects are apportioned to precursor emissions in the unit cost estimates: \( \mathrm{NO}_x \) is a precursor to both tropospheric ozone and fine particulates, while \( \mathrm{NO}_2 \) has direct human health impacts and in the short-term \( \mathrm{NO} \) can provide benefits through ozone destruction. McCubbin and Delucchi [46]...
found that NO\textsubscript{x} was the largest vehicle-generated precursor of ambient PM in southern California (though these high NO\textsubscript{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 $\Delta$ is the sign of $MB' + MSC'$ (Equation 21). The value of $MB'$ depends on the location of the demand curve (i.e. the parameter $\gamma$), but it generally is negative at low $q$ and then approaches 0 asymptotically with higher $q$. The $MSC'$ curve starts at 0 at low $q$ and increases non-linearly with $q$. Deriving $\gamma$ from $q$ by assuming $MB(q) = MPC_{direct}(q)$, we can calculate that for $q \geq 1348$ vphpl, $\Delta$ is positive at $q$. A positive $\Delta$ indicates a theoretical preference for price controls (tolls), with a stronger preference for larger absolute values (expected around $q_c$).

The sign of $\Delta$ around $q_c$ (where it is largest) may not be positive for other locations of the MB curve. At $q_c$, $\Delta$ becomes negative if the MB curve shifts sufficiently to the right: $q \geq 3253$ vphpl (an extremely high volume/capacity ratio of 1.5). These results suggest a general preference for price controls over a wide range of $q$. With multiple units (travelers) possessing uncertain MSC, $\Delta$ will further increase (become more positive) with more units if the MSC are poorly correlated [24]. Thus, heterogeneous costs (because of heterogeneous vehicle types or values of time, for example), can also influence the preference for an instrument.

4.3 Case Study of Portland, Oregon

Using the same MSC curves, the observed average peak-period freeway traffic volumes ($q$) for Portland, Oregon are used as a case study. The estimated $q$ is 1,477 vphpl – the average hourly peak period freeway vehicle-miles traveled divided by the number of freeway lane-miles (extracted from the 2009 Urban Mobility Report [1]). As illustrated in Figure 3, an $MB$ curve is generated at $q$ by assuming...
$MB(q) = MPC_{direct}(q)$. 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 $q$).

![Figure 3 Case Study Results](image)

The optimal volume ($q^*$) is 1,275 vphpl: 14% lower than $q$. The Pigouvian tax is $0.17/veh-mi. For context, this tax equates to an additional $3.41/gallon, assuming a vehicle with 20 mpg fuel economy. The welfare loss due to externalities ($q \neq q^*$) is estimated at $36.13/hr/ln-mi, with an MEC of $0.32/veh-mi at $q$ and an average external cost of $0.09/veh-mi. If $MPC_{indirect}$ is included in the tax to achieve $q^*$, then the tax increases by $0.04 to $0.21/veh-mi. The effects of excluding the on-road pollution exposure components of MEC and MPC would be a 4% higher estimated $q^*$ (1.326 vphpl), a 13% lower Pigouvian tax ($0.15/veh-mi), and a residual welfare loss of $2.30/hr/ln-mi (6.4% of the untaxed loss).

There is uncertainty in the private cost components that lead to the un-tolled equilibrium at $q$. As formulated in Equation 6, $MPC_{direct}$ includes private time and fuel costs. Including private on-road exposure costs ($MPC_{indirect}$) or excluding private fuel costs 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 $MPC$ are $0.36, 0.18, and 0.04$ per veh-mi, 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-mi. 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-mi. Thus, the Pigouvian tax changes by only $0.02/veh-mi depending on whether private on-road exposure costs are considered by travelers, but by $0.10/veh-mi depending on whether private fuel costs are considered.

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5 In this way $MPC_{indirect}$ acts as an externality in determining equilibrium, though it is assessed as a private cost.
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 reduces MPC at $q$ by 3% and
MEC by 32%. The new private equilibrium \(MB = MPC_{direct}\) is at \(q = 1.496\) vphpl – a 1.3% increase.
The new \(q^*\) from this equilibrium is 1,310 vphpl, with a Pigouvian tax of $0.14/veh-mi ($0.17/veh-mi if
including \(MPC_{indirect}\)). Considering the new \(q, q^*\), and MEC curves, the new welfare loss in the system
due to inefficient \(q\) is $25.22/hr/ln-mi (30% lower than $36.13/hr/ln-mi). At the higher equilibrium \(q\) the
\(TSC\) decreases 1% ($11.31/hr/ln-mi), with a 15% decrease in total external costs and a 1% \textit{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 \(TSB\) (Equation 2) of $10.73/hr/ln-mi, which, combined with the \(TSC\) reduction, is an
increase in net benefits (social surplus) of $22.03/hr/ln-mi. 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 \textbf{Sensitivity}
To continue the hypothetical analysis, consider the unit cost ranges shown in Table 1. Varying the
cost parameters over this range leads to a \textit{MEC} at \(q_c\) that varies from $0.86/veh-mi to $3.87/veh-mi (from
the base $2.06/veh-mi). 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” value and varying the other parameters, \textit{MEC} at \(q_c\) only varies
from $1.62/veh-mi to $2.35/veh-mi. The cost coefficients also affect the relative importance of the
exposure cost components: private and external exposure costs are 6% and 13% of \textit{MSC} at \(q_c\) when using
the low and high cost coefficients in Table 1, 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), \textit{MEC} at \(q_c\) is calculated as $1.71, $2.07, and $2.79 per veh-mi. Similarly,
the private and external exposure costs are 4%, 18%, and 38% of \textit{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 \textit{MSC}, the range of \(-0.7 \leq \eta_q^d \leq -0.2\) in Table 1 impacts the shape of the MB curve and the case
study results for Portland presented above. Less elastic demand (–0.2) leads to a 7% higher \(q^*\) (1,368
vphpl), a 32% higher Pigouvian tax ($0.23/veh-mi), and a 43% lower welfare loss at \(q\) ($20.43/hr/ln-mi).
In contrast, more elastic demand (–0.7) leads to a 3% lower \(q^*\) (1,231 vphpl), a 12% lower Pigouvian tax
($0.15/veh-mi), and a 18% higher welfare loss at \(q\) ($42.52/hr/ln-mi).

4.5 \textbf{Policy Implications}
The welfare loss that could be eliminated with optimal pricing in the case study ($36.13/hr/ln-mi)
can be annualized to $36,127/ln-mi 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 [47] 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-mi, 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
corridor with a volume/capacity ratio of only 0.7. For a roadway initially at 95% of capacity, \( q = 2090 \) vphl, \( q^* = 1661 \) vphl, and the welfare loss that could be eliminated with first-best tolling is $327/hr/ln-mi. 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, \( q^* = 1719 \) vphl, the welfare loss is $214/hr/ln-mi, 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 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 \( q = 0.95q_c \) can be estimated as a 5% increase in capacity (leading to a 9% reduction in delay, from Schrank and Lomax [48]); the social welfare gain from the capacity increase (without tolling) is $66.63/hr/ln-mi including on-road exposure costs and $64.33/hr/ln-mi without exposure costs. Thus, when on-road exposure costs are considered, the ITS deployment can be justified on a corridor with 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 $6,000 annualized costs per ramp [47]. 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 externalities costs that can be addressed by pricing.

As another policy consideration, the unique effects of heavy-duty or high-emitting vehicles can be taken into account. We here compare the MEC of heavy-duty (HD) vehicles to the MEC of the general mixed vehicle fleet. In terms of external effects, HD vehicles are distinct in their occupation of roadway capacity and their emissions rates. Assuming that HD vehicles use 50% more capacity than other vehicles [49] 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 exposure MEC. To adjust for distinct emissions characteristics affecting the pollution and exposure MEC, average HD vehicle emissions rate parameters are again drawn from previous research [22]; 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, CO, PM2.5, NOx, and HC, respectively.

With these capacity and emissions rate adjustments, the MEC is 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 (only because of higher emissions rates). At low \( q \) without congestion costs, MEC for HD vehicles is around $0.15/veh-mi, roughly on par with current per-mile charges for heavy trucks in Oregon\(^6\) (which are based entirely on infrastructure costs). The time and fuel MEC is 44% greater for HD vehicles at all \( q \) because of the capacity adjustment. At low \( q \), the exposure MEC is 6.5 times greater for HD vehicles and the pollution MEC is 5.2 times greater; at \( q = q_c \), the exposure MEC is 3.0 times greater for HD vehicles and the pollution MEC 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 MEC, which is increasingly caused by delay to other vehicles for \( q \) near \( q_c \). The impact of considering the on-road exposure externality is more important for HD vehicle marginal costs than for the general fleet:

\(^6\) http://www.hotshotcarrier.com/DOToregonhutguide.pdf
including on-road exposure increases \( MEC \) at \( q_c \) by 27% for the mixed fleet, but increases \( MEC \) at \( q_c \) by 53% for HD vehicles.

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 \( MEC \) 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 [50]. In addition to the marginal cost differences, MB 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 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.

5 CONCLUSIONS

The health cost of on-road air pollution exposure is a component of marginal costs in congested traffic conditions 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 regional pollution emissions components. Using a set of parameter values based on the literature, this paper demonstrates that on-road pollution exposure can be a large portion (18%) of marginal 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 health 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 [17], [51]. 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 costs of on-road exposure at capacity can be as little as 4% or as much as 38% of total marginal costs. The estimation of health outcomes due to varying intensity and duration of exposure during travel is particularly challenging. As with other research [35], 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.

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 volume and total private costs, without reducing certain 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 impact on externality costs than net benefits and thus more 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 occupation of roadway capacity. 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%).

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 rates (which require better on-road exposure modeling tools). For emissions such as NO, consideration should be given to the interaction with secondary pollutants such as ozone and the possibility for separation into constituents (i.e. NO and NO₂). Another issue is the proper classification of 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.

6 ACKNOWLEDGEMENTS

The authors would like to thank for their support of this project: the Oregon Transportation Research and Education Consortium and the U.S. National Science Foundation (through the Graduate Research Fellowship Program, Grant No. DGE-1057604). Additionally, thanks are given to the anonymous reviewers who provided valuable feedback for improvement of this paper.

7 REFERENCES


