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International Fuel Tax Assessment: An Application to Chile

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Abstract

Gasoline and diesel fuel are heavily taxed in many developed and some emerging and developing countries. Outside of the United States and Europe, however, there has been little attempt to quantify the external costs of vehicle use, so policymakers lack guidance on whether prevailing tax rates are economically efficient. This paper develops a general approach for estimating motor vehicle externalities, and hence corrective taxes on gasoline and diesel, based on pooling local data with extrapolations from U.S.evidence. The analysis is illustrated for the case of Chile, though it could be applied to other countries.

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Keywords: gasoline tax, diesel tax, externalities, optimal tax, welfare gains, Chile.

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I. Introduction

In many countries, motor vehicle fuels are one of the most heavily-taxed products.[2] At the same time, motor vehicle use is associated with an unusually diverse variety of externalities, including local and global pollution, traffic congestion, traffic accidents, and road damage. Growing alarm about global climate change, relentlessly increasing urban gridlock, and world oil market volatility, along with calls from the G-20 to phase out fossil fuel subsidies, have all heightened interest in the appropriate level of fuel taxation.

Over the last two decades, there has been a major effort to measure the external costs of motor vehicles in the United States and certain European countries.[3] However, there has not been much attempt to estimate external costs for other (in particular, middle- and low-income) countries, so policymakers in many countries may have little guidance on whether their fuels are currently over- or under-priced from an externality perspective. Fuel tax assessments for one country cannot simply be inferred from optimal tax estimates for, say, the United States, as they depend on many local factors (e.g., travel delays, the incidence and composition of highway fatalities, and local valuations of health and travel time).

This paper describes an approach for compiling rough estimates of automobile and (commercial) truck externalities, based on combining local data with extrapolations from U.S. literature. The parameters are easily applied to formulas for (second-best) corrective gasoline and diesel fuel taxes.[4] The analysis is applied to Chile, which is an interesting case study. Its gasoline tax is high relative to rates prevailing in North and South America, but low by OCED standards (see Figure 1). Its lighter taxation of diesel fuel relative to gasoline is especially striking, and even more so because the modest statutory tax shown in Figure 1 is mostly refunded to trucking companies by the government.[5]

Reasonable economists could debate endlessly the details of our approach, not least because, due to data limitations, some assumptions must be based on judgment. Nonetheless, establishing a ballpark estimate of the corrective fuel tax based on plausible first-pass assumptions—one that can be refined over time with improved data—is better than no figure at all. Furthermore, we demonstrate that, for most parameters, alternative assumptions have relatively minor impacts on corrective taxes.

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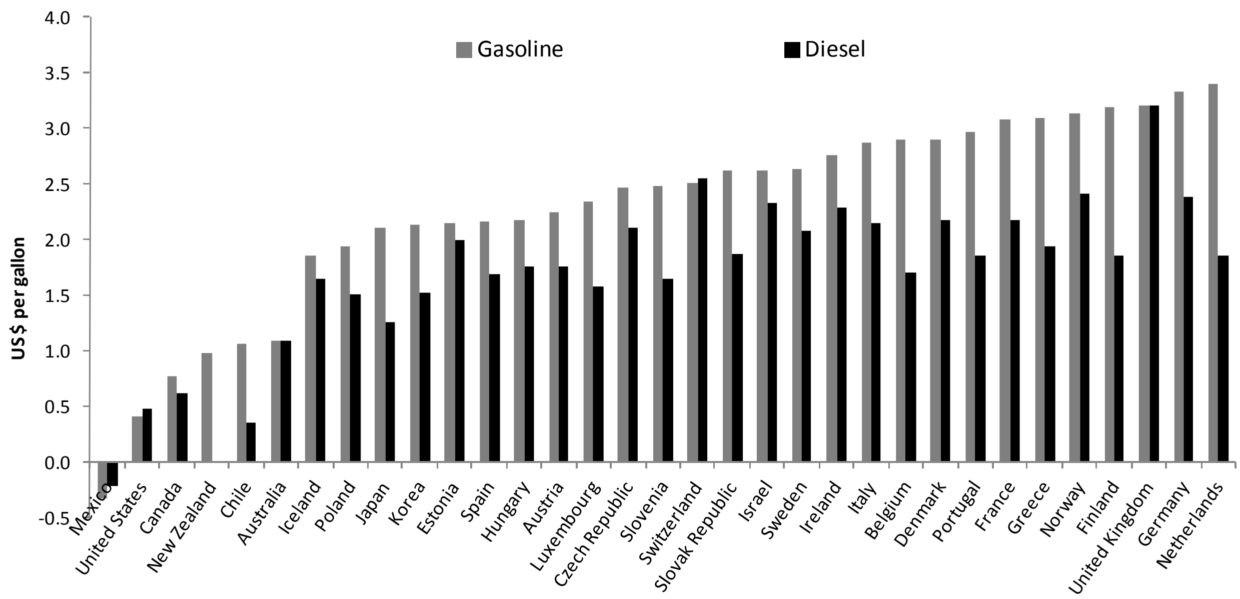
[2] Other countries, however, particularly oil producers, continue to subsidize fuel consumption (e.g., Coady and others, 2010).

[3] See, for example, De Borger and Proost (2001), Parry and others (2007), and Quinet (2004).

[4] Our approach complements another study by Ley and Boccardo (2010). They provide calculations of optimal gasoline taxes for a wide range of countries, though using a less detailed approach than outlined here.

[5] Short-run adjustments in tax rates are made to counteract volatility in oil prices, though these price stabilization mechanisms are beyond our scope.

Figure 1. Excise Taxes on Gasoline and Diesel in OECD Countries in Year 2010



Source: OECD (2010), Figure 2.5.

In our benchmark case the corrective gasoline tax for Chile is $2.35 per gallon,[6] in year 2006 dollars, or about 60 percent greater than the prevailing fuel tax. This estimate is substantially larger than comparable calculations for the United States (e.g., Parry and Small, 2005), even though the valuation of travel time and health risk is lower in Chile. Offsetting these factors is the much higher accident externality, due to the high incidence of pedestrian fatalities, which is a common feature of lower-income countries (Kopits and Cropper, 2008). Moreover, the large share of the country's population residing in Santiago implies a larger share of nationwide mileage occurs under congested conditions, and a larger share of the population is exposed to elevated pollution-health risks. Higher average fuel economy of the car fleet in Chile (compared with the United States) also magnifies congestion and accident benefits per gallon reduction in gasoline.

As for diesel fuel, our benchmark estimate of the corrective tax is $2.09 per gallon (in 2006 dollars). On a per vehicle-mile basis, external costs of trucks are much larger than for cars—for example, trucks take up more road space and contribute more to congestion and, unlike for cars, they impose significant road damage externalities. However, an offsetting factor is that the reduction in truck miles per tax-induced reduction in diesel fuel is much smaller than the reduction in car miles, per tax-induced reduction in gasoline.

The most important source of uncertainty in these corrective tax estimates is the valuation of fatality risks from pollution and accidents—for example, with a low valuation of these risks the

[6] All dollars are U.S. dollars.

corrective gasoline tax falls to $1.53 per gallon. All other assumptions relating to vehicle emission rates, initial fuel economy, behavioral responses, marginal travel delays, etc. have far less significance for corrective tax rates. Thus, our basic qualitative finding—that fuels are, if anything, under-taxed, especially in the case of diesel—appears to be robust.

Two further caveats to the analysis are that we do not explore the possibility of externality mitigation through other instruments (e.g., peak-period congestion pricing), nor linkages between fuel taxes and the broader fiscal system. These and other limitations are discussed at the end of the paper.

The rest of the paper is organized as follows. The next section provides a brief conceptual framework for corrective fuel taxes. Section 3 discusses the methodology for parameter estimation. Section 4 presents the corrective tax results and sensitivity analysis. Section 5 offers concluding remarks.

II. Externality-Correcting Fuel Taxes: Conceptual Issues

Fuel taxes are viewed from the perspective of optimizing benefits from vehicle use, net of external costs. We approximate by assuming that gasoline is used by passenger vehicles and diesel by commercial trucks. Therefore (with one caveat noted below), corrective gasoline taxes depend on auto externalities, while diesel taxes depend on truck externalities.[7]

A. Corrective Gasoline Tax

Parry and Small (2005) derive a formula for the (long-run) optimal gasoline tax using a static, homogeneous agent model, where the agent represents an aggregation over all households in the economy. We discuss, very briefly, an adapted version of their model, the most important difference being that we strip out linkages between gasoline taxes and the broader fiscal system (we do this because we lack reliable data for Chile on labor supply responses, which are needed to assess fiscal linkages).

The model boils down to the following household optimization problem:

$$\text{(1a)} \qquad \underbrace{Max}_{m,v,g,X}\; u(m,v,X,E_G(G),E_M(M)) \quad + \quad \lambda\{I + GOV - (p_G + t_G)G - c(g)v - p_X X\}$$

$$\text{(1b)} \qquad G = gM\,, \qquad M = mv$$

[7] We take the existing road capacity as given. If, in the long run, additional traffic leads to more spending on highway expansion, this would enter into the corrective fuel tax formula, but would be offset because the congestion burden of additional traffic is correspondingly reduced. Our focus is exclusively on fuel taxes. For a discussion of other taxes on vehicle use see, for example, Queiroz (2009).

M denotes vehicle miles traveled by households, equal to the number of autos (v) times miles driven per auto (m). G is aggregate gasoline consumption, equal to gasoline combustion per mile g, or the inverse of fuel economy, times vehicle miles. $E_G(.)$ is externalities that vary in proportion to gasoline use, while $E_M(.)$ is externalities that vary in proportion to vehicle miles (see below). I is private household income (which is fixed) and GOV is a government transfer, which captures the recycling of gasoline tax revenues. $c(g)$ represents the fixed costs of vehicle ownership which are increasing with respect to reductions in g, because more fuel efficient vehicles require the incorporation of (costly) fuel-saving technologies. X is an aggregate of all other goods in the economy. p_G and p_X are the producer prices for gasoline and the general good, which are given (Chile is a price taker in the world oil market). t_G is the excise tax on gasoline. The Lagrange multiplier λ is the marginal utility of income.

Households maximize utility $u(.)$ with respect to v, m, g, and X taking externalities as given and subject to the budget constraint equating income with spending on fuel consumption, vehicles, and other goods.

Fuel-related externalities E_G include CO_2 emissions, while mileage-related externalities E_M include accident risk and road congestion. Following U.S. literature, we attribute road damage externalities (i.e., the costs of roadway wear and tear) to heavy trucks, rather than cars, given that road damage is a sharply increasing function of a vehicle's axle weight (e.g., Small and others, 1989; United States, Federal Highway Administration, 2000, Table 13). Energy security externalities are beyond our scope as they are difficult to define, let alone quantify.[8]

In the absence of regulation, local tailpipe emissions would be proportional to fuel use. However, if all new passenger vehicles are subject to the same emissions-per-mile standards, regardless of their fuel economy, and emissions abatement technologies are fully maintained over the vehicle lifecycle (to satisfy emissions inspections programs for in-use vehicles), emissions become decoupled from fuel economy and vary only with vehicle mileage. The latter assumption seems reasonable for the United States with state-of-the-art emissions control technologies (Fischer and others, 2007). For Chile, where most imported automobiles are initially subject to European ("Euro III") emissions standards, we assume two-thirds of local emissions varies with mileage and one-third with gasoline combustion (corrective fuel tax estimates are not very sensitive to alternative assumptions).[9]

[8] One possible external cost from dependence on a volatile world oil market is the risk of macroeconomic disruptions from oil price shocks that might not (due to market frictions) be fully internalized by the private sector. For the United States, Brown and Huntington (2009) estimate these external costs are fairly modest, however.

[9] Some of the local pollution is also caused by ambient dust, which depends on vehicle mileage rather than fuel economy. Upstream, local emissions leakage during petroleum refining and fuel distribution is an externality that varies with fuel use but the damages are small relative to those from tailpipe emissions (e.g., NRC 2002, pp. 85–86). These emissions are excluded from our pollution damage estimates.

The corrective gasoline tax in the above model, denoted t_G^C, is given by (see Appendix I):

(2a) $$t_G^C = e_G + \beta \cdot e_M / g$$

(2b) $$e_G = -u_{E_G} E'_G / \lambda \,, \qquad e_M = -u_{E_M} E'_M / \lambda \,, \qquad \beta = g \frac{dM / dt_G}{dG / dt_G}$$

e_G and e_M denote the marginal external costs from gasoline use and mileage in dollars per gallon and dollars per vehicle mile, respectively (dividing by λ expresses costs in monetary units). We make the (reasonable) assumption that e_G and e_M are constant over the range of fuel reductions.

The corrective tax in (2a) consists of the marginal external cost from gasoline combustion. It also includes externalities that are proportional to vehicle miles driven, multiplied by two factors. One is fuel economy (averaged across the on-road automobile fleet), which converts costs from dollars per mile into dollars per gallon. Fuel economy rises with higher taxes as households demand more fuel efficient vehicles over the longer run. The second factor, denoted β, is the fraction of the incremental reduction in gasoline use that comes from reduced miles driven, as opposed to improved fuel economy. The smaller is this fraction, the smaller the reduction in mileage-related externalities per gallon reduction in fuel use, implying a smaller contribution of mileage-related externalities to the optimal tax.[10]

We assume the following functional forms:

(3) $$\frac{M}{M^0} = \left(\frac{p_G + t_G}{p_G + t_G^0} \right)^{\eta_M} , \qquad \frac{g}{g^0} = \left(\frac{p_G + t_G}{p_G + t_G^0} \right)^{\eta_g}$$

η_M and η_g denote, respectively, the elasticity of miles driven, and gasoline per mile, with respect to gasoline prices and 0 denotes an initial (currently prevailing) value. The overall gasoline demand elasticity, denoted η_G, is the sum of these individual elasticities, $\eta_G = \eta_M + \eta_g$ (this is easily verified through differentiating the expression for gasoline in (1b)). We take all elasticities as constant (a common assumption), which in turn implies β is also constant.

The welfare gains (W_G) from raising the gasoline tax from an initial level to its corrective level are given by (see Appendix I):

(4) $$W_G = -\int_{t_G^0}^{t_G^C} (t_G^C - t_G) \frac{dG}{dt_G} dt_G$$

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[10] In an extreme case, if all of the incremental reduction in fuel use comes from improved fuel economy, and none from reduced driving, then $\beta = 0$ and mileage-related externalities would play no role in the corrective gasoline tax.

W_G is the difference between the corrective and prevailing tax rate, integrated over the reduction in gasoline demand.

B. Corrective Diesel Tax

Our corrective diesel fuel tax is also derived from a highly simplified model. In particular, we ignore the feedback effect of reduced truck driving on encouraging automobile use via a reduction in road congestion (Calthrop and others, 2007). However, the resulting increase in automobile externalities has a relatively modest impact on the corrective diesel fuel tax, especially if gasoline taxes are raised in tandem with diesel taxes (Parry, 2008, Table 3).[11]

In this model, the household optimization problem is given by:

(5a) $$\underbrace{Max}_{T,X}\, u(T, X, E_F(F), E_T(T)) \quad + \quad \delta\{I + GOV - p_T T - p_X X\}$$

(5b) $$F = fT$$

(5c) $$p_T = (p_F + t_F)f + k(f) + \overline{p}_T$$

T denotes goods whose production and distribution involves a given amount of shipping by trucks, where units are normalized so that T is also truck miles. X is a general good whose production and consumption involves minimal transportation. E_F and E_T are externalities that vary in proportion to diesel fuel consumption and truck mileage respectively, where fuel consumption is the product of mileage and fuel per mile, f. Households choose T and X taking externalities as given, subject to the budget constraint and respective product prices p_T and p_X (δ is a Lagrange multiplier).

In (5c), the unit price of the trucked good consists of fuel costs per mile, where p_F is the pre-tax price of diesel and t_F is the diesel tax. The price also consists of vehicle capital costs expressed on a per mile basis, $k(f)$, where k is increasing with respect to reductions in f due to the incorporation of fuel-saving technologies. $\overline{p}_T$ is non-transportation, unit production costs. Firms choose f to trade off fuel costs per mile with capital costs. As a result, an increase in the diesel tax will increase fuel economy (reduce f), as well as reduce truck mileage, as the tax is passed

[11] We also lump together different types of trucks, rather than considering them separately, even though external costs per vehicle mile will differ across truck classes. For example, external costs per mile on a given road class will be greater for heavy-duty trucks as opposed to light-duty commercial vehicles (the share of these truck types in truck fuel consumption in Chile is currently 65 and 35 percent respectively, according to SII 2008). However, our approach is reasonable if the proportionate reduction in mileage in response to higher diesel taxes is approximately the same for different truck classes. This seems plausible, given that fuel consumption per mile should be roughly proportional to truck weight.

forward into p_T and hence causes households to substitute away from freight-intensive goods towards non-freight-intensive goods.

The corrective diesel fuel tax, denoted t_F^C, is (see Appendix I):

(6a) $$t_F^C = e_F + \alpha \cdot e_T / f$$

(6b) $$e_F = -u_{E_F} E_F' / \delta, \qquad e_T = -u_{E_T} E_T' / \delta, \qquad \alpha = f \frac{dT / dt_F}{dF / dt_F}$$

These expressions are exactly analogous to those in (2a) and (2b) with e_F and e_T the (monetized) marginal external cost of diesel and truck miles respectively, and α is the fraction of the incremental reduction in fuel use that comes from reduced truck mileage, as opposed to better fuel economy. Vehicle noise and roadway wear and tear are potentially significant for trucks and are included in e_T.[12] For trucks, which are also subject to emissions per mile standards in Chile, we again start by assuming that one-third of local emissions are proportional to fuel combustion and two-thirds to miles driven. Functional forms for truck mileage and fuel per mile, and welfare gains from tax reform, are analogous to the previous expressions.

III. Parameter Compilation

This section discusses how parameter values are obtained by pooling local data sources with extrapolations from U.S. evidence and using judgment where data is unavailable. A later sensitivity analysis demonstrates that the valuation of health risks is the most important source of uncertainty, while alternative plausible assumptions for other parameters (e.g., fuel economy or emission rates) have relatively modest implications for corrective fuel taxes. Parameter values are for year 2006 or thereabouts and are summarized in Table 1. All parameters are expressed in U.S. currency.[13]

[12] In contrast, these external costs are relatively small for cars (e.g., UNITED STATES, FEDERAL HIGHWAY ADMINISTRATION 2000).

[13] They can be converted into local currency using a market exchange rate of CLP 550 per $1. This is the average exchange rate that applied during the 2006-2008 period.
See www.latin-focus.com/latinfocus/countries/chile/chlexchg.htm.

Table 1. Benchmark Data and Parameter Assumptions

Data and Parameter Values	Automobiles	Trucks
Initial fuel consumption, million gallons	819.02	898.28
Initial fuel economy, miles/gallon	30.00	8.00
Vehicle miles, billion	24.57	7.19
Initial retail fuel price, $/gallon	4.27	3.17
Initial fuel tax, $/gallon	1.46	0.37
Fuel tax revenue, $billion	1.19	0.33
Externalities from fuel combustion, $/gallon		
local tailpipe emissions (varying with fuel use)	0.29	0.18
Carbon	0.18	0.21
Externalities from driving, $/vehicle mile		
local tailpipe emissions (varying with mileage)	0.02	0.07
congestion	0.04	0.10
accidents	0.06	0.07
noise	0.00	0.01
road damage	0.00	0.08
Fuel demand elasticity	-0.50	-0.50
Milage to fuel price elasticity	0.50	0.60
Fuel economy elasticity	0.25	0.20

Sources: See text and Appendix II for documentation.

A. Fuel Use, Prices, and Mileage Data

Data is typically available for fuel use in the transportation sector, fuel prices, and fuel taxes, but not for (nationwide) vehicle miles of travel or on-road fuel economy. However, if a plausible assumption about fuel economy can be made, mileage is easily inferred. We assume that the fuel economy of the existing automobile fleet in Chile is 30 miles per gallon, that is, somewhere between fuel economy in the United States and Europe.[14] For heavy trucks, we assume fuel economy is 8 miles per gallon, based on U.S. figures for single-unit trucks in Parry (2008, Table 2). For 2007, total gasoline and diesel fuel consumption in Chile was 819 and 898 million gallons respectively, with Santiago accounting for 46.7 and 39.7 percent of these totals, respectively (SII 2008).

[14] We might expect fuel economy to be lower in the United States than Chile, because in the United States almost half of the passenger vehicle fleet consists of light-duty trucks (minivans, sport utility vehicles, pickups), which have lower miles per gallon than cars.

Table 2. Corrective Tax Computations: Benchmark Parameter Values (Year 2006 Dollars)

	Gasoline	Diesel
Corrective fuel tax, $/gal.	**2.35**	**2.09**
Contribution of:		
local tailpipe emissions	0.60	0.53
carbon	0.18	0.21
congestion	0.63	0.52
accidents	0.94	0.39
noise	0	0.03
road damage	0	0.40
Impact of corrective tax:		
Relative to year 2006 tax rate		
Percent reduction in fuel use	9.0	19.5
Percent increase in fuel economy	4.9	9.1
Percent increase in tax revenue	46.8	352.3
Welfare gain, $ million	33.2	150.2
Relative to zero tax rate		
Percent reduction in fuel use	26.2	24.4
Welfare gain, $ million	229.3	222.3

Source: See text for formulas and parameters assumptions underlying these calculations.

Initial retail fuel prices for 2006 are taken to be $4.27 per gallon for gasoline and $3.17 per gallon for diesel, and the respective excise taxes are $1.46 and $0.37 per gallon (SII 2008).[15]

B. External Damages from Local Tailpipe Emissions

For regions outside of Santiago, there is no local data on local pollution damages from automobiles. However, we believe it is reasonable for a first pass to extrapolate local pollution damages from the United States, after adjusting for differences in the value of statistical life (VSL)—given that damages are heavily dominated by mortality effects—and in vehicle emission rates. This procedure is described in Appendix II and the end result is damages of $0.007 per mile. This is based on an assumed VSL of $1.6 million for Chile, extrapolated from U.S. VSL estimates, though as discussed later there is much dispute over this value.

[15] Fuels are also subject to value added taxes (VAT). However, VAT does not count towards the optimal fuel tax as it raises the price of goods in general rather than just fuels.

For Santiago, we might expect much larger damages given its high population density and that meteorological and topographical conditions are especially favorable to pollution formation. Rizzi (2008a) provides detailed local evidence on pollution-health impacts for Santiago. This study is in turn based on a Chilean study, Cifuentes (2001), of mortality and morbidity related to PM and ozone exposure in Santiago in the late 1990s. Using that study, we compute damage estimates of $0.06 per mile (Appendix II). Weighting damages for Santiago and the rest of the country by the respective mileage shares (assumed to be the same as the fuel consumption shares) gives a nationwide pollution cost of $0.03 per mile for Chile. As noted above, we apportion two-thirds of this cost to mileage and one-third to fuel use, to obtain the figures in Table 1.

We assume pollution damage costs for trucks, on a per mile basis, are 3.4 times those for cars. This is based on our own calculations for Santiago (see Appendix II) and it is also consistent with estimates of relative car/truck damage estimates for the United States in Federal Highway Administration (2000), Table 13.

C. Global Pollution

Combusting a gallon of gasoline and diesel fuel produces 0.009 and 0.010 tons of CO_2, respectively.[16] Worldwide damages from the future global warming potential of these emissions (e.g., from agricultural impacts, defense against sea level rise, health effects from the possible spread of tropical disease, damage risks from more extreme climate scenarios) are highly contentious. This reflects different views on the appropriate discount rate, the handling of low-probability/extreme damage outcomes, the valuation of ecosystem damage, and so on. Nonetheless, we think it is reasonable to follow a thorough assessment of available evidence by multiple U.S. government agencies (U.S. Interagency Working Group on Social Costs of Carbon, 2010). They recommended a central damage value of $21 per ton of CO_2 for 2010 emissions (in year 2007 dollars) with low and high cases (which we use for sensitivity analysis) of $5 and $65 per ton.

D. Congestion

Marginal congestion costs depend on the marginal delay (i.e., the increase in delay to other road users due to the added congestion caused by one extra vehicle mile) and the value of travel time (VOT).

An approximation for the marginal delay (averaged across a region) can be inferred from data on average delay, and an assumption about the functional relation between marginal and average delay implied by speed/traffic flow curves (Lindsay and Verhoef, 2000; and Small and Verhoef, 2007, Ch. 3, discuss these relationships). For Santiago, we obtain an estimate of

[16] See http://bioenergy.ornl.gov/papers/misc/energy_conv.html.

average delay at peak and off-peak periods, by comparing observed travels speeds with speed under free-flow conditions. And we obtain marginal delay from average delay using the "Bureau of Public Roads" speed/flow relation, which is widely used in traffic engineering models. As detailed in Appendix II, this procedure yields a marginal delay for Santiago of 0.035 hours per auto mile (averaged across time of day).

As for the rest of Chile, we assume no congestion in rural areas. For other urban centers, we assume average travel speeds (with a shorter rush hour duration) are comparable to those outside of the (congested) downtown core in Santiago. Reasonable information on these speeds is available from a local transportation model for Santiago, and based on this data, marginal delays in other cities are calculated at 32 percent of those for Santiago as a whole. Weighting regional marginal delays by respective nationwide mileage shares yields a marginal delay of 0.022 hours per mile, averaged across the nation (see Appendix II).

As for the VOT, we use a central value of \$2.7 per hour and a range of \$1.5–\$4.5 per hour for sensitivity analysis. The central figure is obtained by extrapolating evidence on the VOT for the United States, while the low end of the range encompasses current government practice in Chile and the upper end some evidence from local studies (see Appendix II).

Combining our central VOT and marginal delay yields a marginal external congestion cost of \$0.06 per mile. One further complication is that driving on relatively congested roads (which are heavily used by commuters) is typically less sensitive to gasoline prices than driving on relatively uncongested roads. Thus, the congestion benefits from a given reduction in nationwide mileage are smaller than they would be if driving on congested and uncongested roads were equally price sensitive. Based on typical estimates of the relative sensitivity of driving under congested and uncongested conditions, Parry and Small (2005) scaled back nationwide marginal congestion costs by 30 percent. We follow the same procedure to obtain a preferred marginal external congestion cost of \$0.04 per mile.

Finally, based on standard estimates from the literature (e.g., Santos and Fraser, 2006; Santos, 2008) we assume that a vehicle mile by a heavy truck contributes 2.5 times as much to congestion as an extra automobile mile. These estimates take into account the extra road space used by trucks and their slower driving speeds, offset by their greater propensity for off-peak travel.

E. Accidents

Local data on traffic injuries is critical for gauging accident externalities, not least because the incidence of pedestrian/cyclist injuries—a major determinant of externalities—varies dramatically across countries (Kopits and Cropper 2008). As discussed in Appendix II, we start with Chilean accident data for various non-fatal injury classifications, for 2006. We make assumptions about what portion of personal injury, medical costs and property damages associated with these injuries are external (e.g., occupant injury risk in single vehicle collisions is assumed internal). The external components are then monetized using a mixture of local evidence and U.S. extrapolations.

The end result is external cost for a car of $0.06 per mile. Pedestrian/cyclist fatalities alone account for about three-quarters of this figure, therefore alternative assumptions about the extent to which medical costs, property damages, and injuries in multi-vehicle collisions are external versus internal have a relatively modest impact on the external cost estimate.

As for trucks, we follow de Palma et al. (2008), Parry (2008), and Federal Highway Administration (2000), in assuming that external accident costs are 25 percent greater than for cars, implying an externality of $0.07 per mile.[17]

F. Road Damage and Noise

Road damage costs for trucks are estimated at $0.08 per mile and noise costs a much smaller $0.01 per mile. Appendix II provides details on these calculations. Road damage is inferred from government expenditures on road maintenance, after attributing a portion of these costs to other vehicles and other factors, while noise costs are obtained from U.S. estimates (after making an adjustment for income and the share of urban versus rural driving).

G. Elasticities

According to reviews by Goodwin and others (2004) and Glaister and Graham (2002) the long run gasoline demand elasticity for countries like the United States is around –0.6, though a recent, widely cited, study by Small and Van Dender (2006) suggests a somewhat smaller size elasticity of –0.4. About 40 or 50 percent of the elasticity is attributed to reduced mileage, as opposed to long run vehicle fuel economy improvements. Given the wider availability of transit alternatives, we might expect mileage to be moderately more price-responsive in Chile than the United States.[18] We choose a value of –0.5 for the gasoline price elasticity, with the assumed response split equally between improved fuel economy and reduced driving.

The limited evidence available on diesel fuel elasticities for heavy trucks for high-income countries suggests that they are roughly comparable in magnitude to gasoline demand elasticities (e.g., Dahl 1993, pp. 122–23). It seems plausible that the mileage component of the elasticity is somewhat larger for diesel than for gasoline, as technological opportunities for improving fuel economy are more limited for trucks than for cars given the high power requirements necessary

[17] Due to their much greater weight, we would expect heavy-duty trucks to pose far greater risks than autos to other vehicles and their occupants in a collision (for given travel speeds). However, counteracting this is that trucks are driven by professionals, typically at lower speeds, and more frequently at night, than cars, and therefore crash less often.

[18] The only estimate we are aware of that uses local data is Rogat and Sterner (1998), who put the gasoline demand elasticity for Chile at –0.43.

to move freight. We use a diesel fuel price elasticity of –0.5, with 60 percent of the response from changes in mileage, and 40 percent from changes in fuel economy.

IV. Corrective Fuel Tax Calculations

A. Benchmark Results

The top half of Table 2 presents the corrective tax calculations under our benchmark parameter assumptions.

Gasoline tax

The corrective gasoline tax is $2.35 per gallon, which is 60 percent larger than the rate prevailing in 2006. Traffic accidents account for 40 percent of the tax, congestion 27 percent, local tailpipe emissions 26 percent, and global warming 8 percent.

This corrective tax estimate is higher than comparable estimates for the United States (e.g., Parry and Small 2005). At first glance, this seems surprising given the lower valuation of health risks and travel time in Chile. However, one offsetting factor is that accident externalities are much larger in Chile, due to the much higher incidence of pedestrian/cyclist fatalities. In addition, despite the lower VOT in Chile, our nationwide figure for marginal congestion costs is comparable to that in U.S. studies, because a larger share of nationwide driving occurs under highly congested conditions (in Santiago). Similarly, although the assumed VSL for Chile is lower, the (nationwide) pollution-mortality rate is greater, given the large share of the population residing in Santiago and therefore exposed to elevated risks. Yet another factor is that the assumed miles per gallon is larger in Chile than the United States. This implies a greater reduction in mileage per gallon of fuel saved, which in turn magnifies the mileage-related externality benefits, particularly congestion and accidents (through lowering g in equation (2a)).

Diesel tax

The corrective diesel fuel tax in the benchmark case is $2.09 gallon. This is smaller than the corrective gasoline tax, but only moderately so—external cost considerations do not warrant the current, and strikingly large, tax preference for diesel over gasoline.

Local and global pollution contribute a roughly similar amount to the corrective tax for either fuel. However, unlike for gasoline, road damage contributes a significant amount ($0.40 per gallon) to the diesel tax (the contribution from noise is small). On the other hand, an offsetting factor is that trucks travel a shorter distance on a gallon of fuel than cars, which substantially reduces the mileage-related externalities per gallon of diesel fuel reduction. This is particularly the case for accidents, which contribute 39 cents to the corrective diesel tax compared with 94 cents for the corrective gasoline tax. Congestion also contributes less, but only moderately so

(52 cents to the diesel tax and 63 cents to the gasoline tax), given our assumption that a truck mile contributes two and a half times the congestion as a car mile. Again, this corrective tax estimate is higher than for comparable estimates for the United States (e.g., Parry, 2008), for similar reasons to those for the gasoline tax.

Impacts of tax reform

Also indicated in the lower half of Table 2 is the impact of tax reform. Raising taxes from their 2006 levels to their corrective levels in the benchmark case would reduce (long-run) gasoline and diesel use by an estimated 9.0 and 19.5 percent respectively (the latter reduction is much larger due to the much larger difference between corrective and initial tax rates). The fuel economy increase is 4.9 percent for cars and 9.1 percent for trucks. Under corrective taxes, gasoline tax revenue increases 47 percent above 2006 levels while diesel tax revenues are 3.5 times as large. Annual welfare gains from raising taxes on gasoline and diesel to their corrective levels are $33.2 million and $150.2 million, respectively.

If initial tax rates were zero (and initial fuel consumption were proportionately larger according to equation (4)), fuel reductions from implementing the corrective tax would be in the order of 25 percent for either fuel. Estimated welfare gains (from the corrective fuel tax relative to no tax) would be substantially larger at $229 million and $222 million, respectively.

B. Sensitivity Analysis

Table 3 indicates corrective fuel taxes under a wide range of alternative parameter scenarios (where parameters are varied one at a time).

Results are most sensitive to the VSL. As discussed in Appendix II, a plausible range of values for the Chilean VSL could be anywhere from about $0.8 million to $3.1 million. Using the higher VSL almost doubles local pollution and accident externalities and the corrective gasoline and diesel taxes increase to $4.00 per gallon and $3.02 per gallon respectively. On the other hand, under the low VSL value, the corrective gasoline and diesel taxes fall to $1.53 per gallon and $1.60 per gallon, respectively.

In the remaining cases in Table 3, alternative parameter assumptions can have significant, but less dramatic, effects on corrective fuel taxes.

Table 3. Corrective Tax Calculations: Alternative Parameter Values

	Gasoline tax, $/gallon	Diesel tax, $/gallon
Benchmark case	2.35	2.09
Alternative value of life assumptions		
VSL = $0.8 million	1.53	1.60
VSL = $3.1 million	4.00	3.02
Alternative global warming damages		
Social cost of carbon = $5 per ton	2.20	1.91
Social cost of carbon = $65 per ton	2.78	2.57
Initial fuel economy		
36 miles per gallon	2.51	2.31
24 miles per gallon	2.20	1.87
Local pollution damages		
Increased 50 percent	2.69	2.37
Decreased 50 percent	2.02	1.81
Travel delay		
Increased 50 percent	2.71	2.37
Decreased 50 percent	2.01	1.81
Alternative value of time assumptions		
VOT = $1.5 per hour	2.05	1.84
VOT = $4.5 per hour	2.83	2.46
Accident externalities		
Increased 50 percent	2.88	2.30
Decreased 50 percent	1.85	1.88
Road damage		
Increased 50 percent	2.35	2.30
Decreased 50 percent	2.35	1.88
Magnitude of fuel price elastcity		
Increased 50 percent	2.41	2.17
Decreased 50 percent	2.31	2.01
Fraction of fuel price elasticity due to reduced mileage		
Gasoline 0.65, diesel 0.75	2.93	2.46
Gasoline 0.35, diesel 0.45	1.76	1.67

Source: Authors’ calculations.

Using a higher value for global warming damages—\$65 per ton of CO_2 instead of \$21 per ton—increases the corrective gasoline tax and diesel tax by \$0.43 and \$0.48 per gallon, respectively.[19]

We vary the initial fuel economy between 24 and 36 miles per gallon for cars and between 6.4 and 9.6 miles per gallon for trucks. This causes the corrective fuel taxes to vary by about + or –6 percent for cars and + or –10 percent for trucks as higher (lower) fuel economy magnifies (dampens) the contribution of mileage-related externalities.

Increasing and decreasing local pollution damages by up to 50 percent causes the corrective fuel taxes to vary by up to about + or –14 percent, while increasing and decreasing marginal travel delay by up to 50 percent causes corrective taxes to vary by up to about + or – 15 percent. Using the smaller value for the VOT (\$1.50 instead of \$2.70 per hour) decreases both corrective taxes by about 12 percent. Varying accident externalities by + and –50 percent causes the corrective gasoline tax to vary by about + and –20 percent and the corrective diesel tax to vary between about + and –10 percent. Varying road damage + and –50 percent causes the corrective diesel tax to vary between + and –10 percent.

The results are fairly insensitive to varying own-price fuel elasticities, with mileage and fuel economy elasticities changing in the same proportion. More significant is, for a given overall fuel price elasticity, the relative price responsiveness of mileage and fuel economy (which determines β and α in equations (2) and (6)). As indicated in the last row of Table 3, varying the fraction of the gasoline elasticity that is due to reduced mileage from 0.35 to 0.65 causes the corrective gasoline tax to vary between about + and –25 percent. And varying the fraction of the diesel fuel price elasticity due to mileage between 0.45 and 0.75 causes the corrective diesel tax to vary between approximately + and –20 percent.

V. CONCLUSION

This paper presents a methodology for compiling estimates of parameters needed to assess corrective motor fuel taxes for a middle-income country. We use Chile as an illustration, though we believe the paper provides a useful template for approximately gauging corrective fuel taxes in other countries at similar levels of development (at least those with comparable data sources).

For Chile, the corrective gasoline and diesel taxes are \$2.35 and \$2.09 per gallon in the benchmark case—higher than typical tax rates prevailing in Western Hemisphere countries, but lower than typical rates in Western Europe. Despite lower valuations of health risks and travel delays, the corrective fuel tax estimates for Chile are larger than comparable estimates for the United States. This is due to a mix of factors, including the higher incidence of pedestrian

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[19] These increases are slightly larger than the increase in CO_2 damages per gallon of gasoline (\$0.39 per gallon) and per gallon of diesel (\$0.45 per gallon), as higher taxes increase fuel economy, which in turn magnifies the contribution of mile-related externalities (again, though lowering g in (2a) and f in (6a)).

fatalities in Chile, as well as the high proportion of its population residing and driving in the metropolitan Santiago region, where conditions are conducive to pollution formation and roads are clogged.

Again, we emphasize that the analysis is only meant to provide a first-pass assessment. There is plenty of scope for parameter estimates to improve with better data, though, aside from the (contentious) valuation of mortality risk, we conjecture that, in most cases, refinements will likely have a non-dramatic impact on corrective fuel tax estimates.

Another caveat is that there are far more efficient instruments than fuel taxes for addressing some of the key externalities. Traffic congestion is better addressed through per mile tolls on congested roads that rise and fall during the course of the rush hour (e.g., Santos, 2004). These taxes would exploit all of the possible behavioral responses for reducing congestion—encouraging people to commute earlier or later to avoid the peak of the rush hour, to car pool, to use public transport rather than drive, to reduce their overall number of trips, to re-locate jobs out of busy downtown areas, etc. Accident externalities can be efficiently reduced through a transition to pay-as-you drive auto insurance (Bordhoff and Noel 2008). Under this approach, a driver's insurance payment is the product of their annual miles driven and a per mile charge that depends on their risk factor (as determined by their age, prior crash record, etc.) so drivers with greatest accident risk have most incentive to conserve on vehicle use. However, until congestion and accident externalities are comprehensively internalized through other instruments, in the interim it is entirely appropriate to include them in fuel tax assessment.[20]

Our analysis abstracts from linkages between fuel taxes and the broader fiscal system, particularly tax distortions in the labor market which depress the level of work effort below economically efficient levels. These interactions take two forms (e.g., Goulder, 1995). First is the potential efficiency gain from using fuel tax revenues to reduce distortionary taxes, or fund socially productive public projects. Second is an efficiency loss to the extent that higher transportation prices cause a (slight) contraction in economic activity and hence labor supply. For the United States, West and Williams (2007) find evidence that the former effect exceeds the latter—in other words, gasoline is a relatively weak substitute for leisure—implying that the optimal (revenue-neutral) tax is somewhat higher than the corrective tax. However, reliable evidence on labor supply responses to income and fuel taxes, that are needed to make these types of adjustments to optimal fuel tax estimates for Chile, is not available at present.

Finally, the distributional argument against higher fuel taxes in Chile seems open to question given that, according to CASEN (2006), in 2006, only 9.4 percent of households in the bottom income decile owned a car, compared with 72.7 percent for the top-income decile. Furthermore, it could be argued that holding down fuel taxes below levels warranted on externality grounds is

[20] Road tolling is emerging in Chile—for example, the major north-south toll route in Santiago (the Autopista Central) was opened in 2004. However, such tolls affect a small portion of roads nationwide at present and would therefore imply only a modest downward adjustment in the optimal fuel tax.

an inefficient way to help poor households, as this benefits all households, not just the target group. In general, distributional goals are better met through more targeted provisions in the tax and benefit system, education policy, housing policy, and so on.

Appendix I. Analytical Derivations

Deriving Equation (2): The corrective gasoline tax. The optimal tax is derived using a standard two-step procedure. First, we solve the household optimization problem in equation (1) above, where externalities, and government variables, are taken as given. This yields the first order conditions:

$$\text{(A1)}\quad \frac{u_m}{v} = \lambda(p_G + t_G)g\,, \quad u_v = \lambda\left[(p_G + t_G)gm + c\right],$$
$$-c'(g) = (p_G + t_G)m\,, \quad u_X = \lambda p_X$$

The second step is to totally differentiate the household's indirect utility function, which is simply equivalent to the expression in (1), with respect to the gasoline tax. In this step, economy-wide changes in externalities and the government transfer are taken into account. Using the first order conditions in (A1) to eliminate terms in dm/dt_G, dv/dt_G, dg/dt_G, and dX/dt_G, the total differential is given by:

$$\text{(A2)}\quad u_{E_G} E'_G \frac{dG}{dt_G} + u_{E_M} E'_M \frac{dM}{dt_G} + \lambda\left\{\frac{dGOV}{dt_G} - G\right\}$$

The government budget constraint, equating spending with fuel tax revenue, is $GOV = t_G G$. Totally differentiating this constraint gives:

$$\text{(A3)}\quad \frac{dGOV}{dt_G} = G + t_G \frac{dG}{dt_G}$$

To obtain the corrective tax we equate (A2) to zero and substitute (A3) to give:

$$\text{(A4)}\quad t_G^C = -\frac{u_{E_G}}{\lambda} E'_G - \frac{u_{E_M}}{\lambda} E'_M \frac{dM/dt_G}{dG/dt_G}$$

From differentiating the expression for gasoline use in equation (1b) above:

$$\text{(A5)}\quad \frac{dG}{dt_G} = g\frac{dM}{dt_G} + M\frac{dg}{dt_G}$$

Thus, the fraction of the reduction in gasoline use that is due to reduced mileage is

(A6) $$\beta = \frac{gdM / dt_G}{dG / dt_G}$$

Substituting (A6) and expressions in (2b) in (A4), gives the corrective tax formula in equation (2a) above.

Deriving Equation (4): Welfare gains from tax reform. Expression (A2) gives the welfare gain from an incremental increase in the gasoline tax. Dividing by λ to express in monetary terms, and substituting from (A3) and (2b), gives:

(A7) $$-e_G \frac{dG}{dt_G} - e_M \frac{dM}{dt_G} + t_G \frac{dG}{dt_G}$$

Using the definitions of t_G^C and β in (2) gives

(A8) $$-(t_G^c - t_G)\frac{dG}{dt_G}$$

Integrating over the tax rise gives the total welfare gain in equation (4) above.

Deriving Equation (6): The corrective diesel tax.

The household optimization in equation (5) yields the first order conditions:

(A9) $$u_T = \delta p_T , \qquad u_X = \delta p_X$$

And the optimization over fuel intensity by producers (i.e., the minimization of per unit trucking costs in (5c)) yields:

(A10) $$t_F + p_F = -k'(f)$$

Differentiating the household's indirect utility function (equivalent to the expression in (5a)), accounting for changes in externalities, and using (A9) to eliminate terms in dT / dt_F and dX / dt_F gives:

$$\text{(A11)} \quad u_{E_F} E'_F \frac{dF}{dt_F} + u_{E_T} E'_T \frac{dT}{dt_F} + \lambda \left\{ \frac{dGOV}{dt_F} - T \frac{dp_T}{dt_F} \right\}$$

Differentiating the government budget constraint, $GOV = t_F F$, gives

$$\text{(A12)} \quad \frac{dGOV}{dt_F} = F + t_F \frac{dF}{dt_F}$$

The impact of the fuel tax on the price of the trucked good is, from differentiating (5c) and substituting (A10):

$$\text{(A13)} \quad \frac{dp_T}{dt_F} = f$$

Substituting (A12), (A13) and (5b) in (A11), and equating to zero, gives the corrective diesel tax formula defined in (6a) and (6b) above.

Appendix II. Additional Details on External Cost Assessment

A. Pollution

For regions outside of Santiago: extrapolating from U.S. estimates. There is reasonable consensus in the U.S. literature on the overall size of (local) pollution damages from automobiles. A thorough assessment by NRC (2009), Table 3.3, put damages at about \$0.008 per vehicle mile for a gasoline vehicle (excluding emissions during vehicle manufacture), for year 2005 (in year 2007 dollars). Mortality effects for sensitive groups (seniors and people with pre-existing health conditions) account for about three-quarters of these estimates (other effects include morbidity, reduced visibility, ecosystem impacts, building corrosion, etc.).[21] NRC (2009) assumed a VSL of \$6 million (see also U.S. EPA 2010). To extrapolate the damage figure to Chile (outside of Santiago) we need to consider differences in the VSL and vehicle emission rates.

For the VSL, we extrapolate U.S. estimates using the following, commonly used formula (e.g., Cifuentes and others 2005, pp. 40–41):

$$\text{(C1)} \qquad VSL_{Chile} = VSL_{US} \cdot \left(\frac{I_{Chile}}{I_{US}} \right)^{\eta_{VSL}}$$

where I_Y denotes real per capita income in county Y and η_{VSL} is the elasticity of VSL with respect to income. From World Bank (2008), I_{Chile} / I_{US} is (\$13,000/\$48,150=) 0.27.[22]

Empirical literature on the income elasticity of the VSL is unsettled, with estimates varying between about 0.5 and 1.5. This suggests a plausible range for Chile of \$0.8 million to \$3.1 million, with a benchmark value (when the VSL/income elasticity is unity) of \$1.6 million.[23]

[21] Damages are easily dominated by particulate matter (rather than ozone), some emitted directly, and some formed in the atmosphere from nitrogen oxides and hydrocarbons.

[22] This is based on purchasing power parity rather than market exchange rates to account for the greater spending power of income in Chile due to lower (non-tradable) goods prices.

[23] Viscusi and Aldy (2003) and Miller (2000) estimate the VSL/income elasticity at about 0.5 and unity respectively. Alan Krupnick, an expert on the issue, recommended we use a range of 0.5 to 1.0 (personal communication, November 2008). However, pending additional studies, Hammitt and Robinson (2011) suggest using a range of 1.0 to 1.5 to extrapolate VSL values for middle and low income countries. This is based on some recent studies suggesting the VSL/income elasticity might be greater than unity (e.g., Cropper and Sahin, 2009; Hammitt and others, 2000). Our lower bound value is more in line with a local, stated preference study, after updating (Cifuentes and others, 2000).

Based on a personal communication with Luis Cifuentes (November, 2008) we assume current auto emission rates in Chile are the same as those applying in the United States in 1992, or three times the current U.S. rates (United States, Bureau of Transportation Statistics, 2008, Table 4.38).[24]

Applying our (central case) adjustments for the VSL and emission rates yields a damage of $0.0065 per vehicle mile.

Table 4. Pollution Damage Calculations for Santiago

Health Effect	Instances of Health Effect		Cost per Effect ($ thousands)
	Automobiles	Trucks	
Acute mortality	83.1	69.7	1600
Long-term mortality	239.9	199.7	1600
Hospital admissions	332.3	276.7	1.45
Emergency room admissions	3376.8	2814.0	0.18
Chronic bronchitis	514.6	428.8	52.7
Acute bronchitis	876.4	730.3	0.03
Asthma attacks	18693.0	15577.5	0.03
Work days lost	157450.0	131320.0	0.03
Restricted activity days and symptom days	538010.0	448230.0	0.01
Total health cost, $ million	555.6	463.4	
Materials damage, $million	85.0	73.0	
Total pollution cost, $million	640.6	536.4	
Fraction of cost due to mortality	0.8	0.8	
Pollution cost, US$/mile	0.1	0.2	

Source: Rizzi (2008a) and personal communication, Luis Cifuentes, December 2008.

For Santiago. We begin with Rizzi's (2008a) estimated incidences of mortality and morbidity (for year 2001) in Santiago that are attributed to trucks and automobiles, as shown in the first two

[24] Although vehicles imported into Chile are now subject to approximately equivalent emissions standards as new vehicles in the United States, emissions standards were introduced, and ramped up, far later in Chile than the United States. Consequently, in 2006 there was a significantly greater share of older, highly emissions-intensive vehicles (without catalytic converters) in the vehicle fleet. Given that these vehicles are still relatively small in size, they do not reduce average fleet fuel economy by much, but they do substantially raise overall emission rates for the fleet. Moreover, as noted in the text, assuming emission rates are 50 percent higher or 50 percent lower affects the correct fuel tax estimates only moderately.

columns of the upper part of Table B1.[25] The numbers here are based on both PM and ozone exposure, with basic morbidity and mortality estimates from a Chilean study, Cifuentes and others (2001), which developed local air quality and dose-response models for Santiago. The figures in Table B1 account for a downward adjustment of one-third recommended by Luis Cifuentes (personal communication, December 2008) reflecting more recent U.S.evidence suggesting that the relationship between health impacts and pollution concentrations is better represented by a concave (log-linear) rather than linear function (Pope and others, 2004, 2006).

In Table B1, we monetize these effects with our central VSL value. Morbidity effects, for example, instances of asthma and bronchitis, are valued by the respective unit costs in Rizzi (2008a). Overall pollution damages are not very sensitive to alternative assumptions for valuing morbidity.

Multiplying instances of health impacts by the cost per impact, and aggregating gives total annual health costs of \$0.49 or \$0.84 billion for automobiles and \$0.42 billion or \$0.72 billion for trucks. In Table B1 we also include corrosion to buildings and other objects from pollution, based on Rizzi (2008a), Table 6.[26] These effects amount to 7–14 percent of health damages.

Dividing the total pollution damage figures in Table B1 by distance travelled by automobiles and trucks in Santiago (11,474 and 2,853 million miles, respectively) gives damages of \$0.06 per mile for automobiles and \$0.19 per mile for trucks.

B. Congestion

Average delay for Santiago. We obtain travel speeds for Santiago from the ESTRAUS model.[27] Based on our own simulations of this model, the average automobile travel speeds under peak, off-peak, and free-flow traffic conditions in the Santiago metropolitan area are 21.2, 24.5 and 28.5 miles per hour, respectively. Inverting these figures, and comparing actual and free-flow travel times, we obtain average delays due to congestion of 0.012 hours per mile and 0.006 hours per mile, for peak and off-peak travel respectively. About 50 percent of auto travel occurs during

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[25] The data only allows an assessment of short-term or acute mortality effects. Long-term mortality effects occurring with a lag in the lifecycle, following an extensive period of pollution intake, are inferred based on the ratio of long-term to short-term mortality from U.S. literature.

[26] Rizzi's numbers are based on a separate Chilean study, Universidad de Chile (2002). This study uses data on maintenance expenditures for building facades (for wood, concrete, and windows) between relatively clean and relatively polluted areas to infer corrosion impacts. This study was conducted in the late 1990s. The estimates have been increased by 30 percent to reflect the approximate increase in valuation of such damages up to 2006, resulting from real estate value increases and cost increases for building repair.

[27] This model provides a detailed and carefully calibrated representation of the Santiago road transportation network (see de Cea Ch. And others, 2003 for a description of the model).

the peak period and 50 percent at off-peak (including weekends) hence delay averaged over time of day is 0.009 hours per mile.[28]

Ratio of marginal to average delay. The most commonly used functional form relating travel time per mile (the inverse of speed), denoted T, to traffic volume (vehicles per lane mile per hour), denoted V, is:

$$\text{(C2)} \quad T = T_f\{1 + \alpha V^{\theta}\}$$

α and θ are parameters and T_f is time per mile when traffic is free flowing. A typical value for the exponent θ is 2.5–5.0 (Small, 1992, pp. 70–71). With $\alpha = 0.15$ and $\theta = 4.0$, equation (C2) is the Bureau of Public Roads formula, which is widely used in traffic engineering models. Subtracting T_f from (C2) and dividing by V gives the delay per vehicle mile due to congestion, $T_f \alpha V^{\theta-1}$. And subtracting T_f from (C2), and differentiating, the marginal delay per vehicle mile is $\theta T_f \alpha V^{\theta-1}$. Hence the ratio of the marginal to average delay is θ, or 4 with the Bureau of Public Roads formula. Quadrupling average delay gives a marginal delay of 0.035 hours per mile.

Nationwide delay. Santiago accounts for about half of nationwide car mileage, other urban areas a further 40 percent, and rural areas 10 percent (Sii, 2008). We assume no congestion in rural areas. In other urban areas, we assume travel speeds averaged across the peak period are comparable to those in Santiago, outside of the congested downtown core. Based on our simulations of the ESTRAUS model, average (and hence marginal) delays in other cities are 32 percent of those for Santiago as a whole (one reason being the shorter duration of rush hour). Thus, weighting marginal delays in Santiago, other urban areas, and rural areas by their respective mileage shares gives a nationwide marginal delay of 0.022 hours per mile.

Value of travel time. Reviews of empirical literature for the United States and some European countries recommend a VOT for peak-period auto travel of about half the market wage (e.g., Waters, 1996; United States, Department of Transportation, 1997; Mackie and others, 2003). Based on average urban wage rates in BLS (2006), Table 1, this implies a U.S.VOT of $10 per hour.

To extrapolate to Chile, we multiply by the ratio of the Chilean to U.S.income (0.27) raised to the power of the VOT/income elasticity. Estimates of this elasticity for high-income countries are typically around unity (e.g., Wardman, 2001; Mackie and others, 2003), which gives a VOT for Chile of $2.7 per hour. Based on VOT values from other sources, we consider a range of $1.5 to $4.5 per hour for sensitivity analysis.[29]

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[28] This information comes from transport surveys (e.g., traffic counts, roadside interviews) used in the ESTRAUS model.

[29] Our central value is broadly consistent with Jara-Díaz et al. (2008): they estimate a VOT of $2.9 per hour (in general, rather than specifically for travel) using Chilean data. Current government practice in Chile, however, is to

C. Accidents

According to police-reported data, in 2006 there were 1,652 road deaths in Chile, with pedestrians/cyclists and car/truck occupants, accounting for 55 percent and 41 percent of these deaths, respectively.[30] We make the common assumption that all pedestrian/cyclist deaths are external. Of the vehicle occupant deaths, we assume, as in the United States, that half of these are in single-vehicle accidents, and represent internalized risks. To what extent injuries in multi-vehicle collisions are external is unsettled. All else constant, the presence of an extra vehicle on the road raises the likelihood that other vehicles will be involved in a collision, but a given collision will be less severe if people drive slower or more carefully in heavier traffic. Following Parry (2004) (medium scenario), we assume that half of the remaining deaths in multi-vehicle collisions represent an external cost.

The 1,078 external fatalities are valued using our central case VSL, giving a cost of $1.72 billion.

There are various other dimensions to accident costs that we include, but, at least for Chile, these costs are small relative to those from external fatalities. Therefore, the detailed assumptions made below are not especially important.

There were 6,515, 4,400 and 36,020 serious, less-serious, and light injuries in police-reported road accidents in 2006.[31] These injuries are not broken out according to pedestrian/cyclists and vehicle occupants, though we would expect pedestrians to account for a much smaller share of these nonfatal injuries than their share in fatalities, given that a car/pedestrian collision is far more likely to cause a fatality than a car/car collision. We assume that 32 percent of non-fatal injuries are external (compared with 65 percent for fatalities).

We value the personal suffering costs from nonfatal injuries using two sources. First, we take the personal cost of suffering from a serious, less-serious, and light injury from the corresponding figure for disabling, evident, and possible injuries in Parry (2004, Table 2), scaled by the Chile/U.S. VSL (0.27). These costs are $0.023 million, $0.005 million, and $0.004 million, respectively. Adding up, and monetizing, external non-fatal injuries produce an additional external cost of $0.10 billion. Second, Rizzi (2008b) values serious, less-serious, and light accident injuries at $0.074 million, $0.018 million, and $0.004 million, respectively. These values combine medical costs and personal injury costs, though they are not decomposed in the

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use a much lower VOT (e.g., Ministerio de Planificación 2008) of around $1.5 per hour. On the other hand, according to Luis Rizzi (personal communication, December 2008) some other unpublished estimates put the VOT for automobile travel in Chile at over $4.4 per hour, reflecting the heavy concentration of car ownership and use among high-income groups.

[30] Figures are from www.conaset.cl.

[31] Again, see www.conaset.cl. These figures are conservative as they exclude traffic accidents that are not reported to the police. In fact, non-fatal traffic injury data may not be very reliable, even in the United States (e.g., Miller 1997).

data. Based on Parry (2004, Table 2), we assume that medical costs and personal injury costs account for 20 percent and 80 percent, respectively, of these figures. Adding up, and monetizing, external non-fatal injuries with these alternative personal cost assumptions gives an additional external cost of $0.18 billion. Splitting the difference between the two estimates gives our preferred external cost of $0.14 billion.

We assume that 85 percent of medical costs for all non-fatal injuries (including injuries in single-vehicle collisions, etc.) are external (they are largely borne by third parties, particularly government medical services). Again, we obtain the total external cost from valuing 85 percent of non-fatal injuries using the medical costs implied by Parry (2004) and by Rizzi (2008b) (in each case medical costs per injury are one-quarter of personal injury costs) and split the difference. This produces an additional external cost of $0.09 billion.

Finally, we assume that 50 percent of property damage costs (from all accidents) are external costs that are borne by insurance companies, rather than individuals (through deductibles, non-insured accidents, elevated premiums following a claim, etc.). Data on traffic accidents involving property damage only (and no injuries) is unavailable: based on Parry (2004, Table 2), we assume the number of these accidents is the same as those involving light injuries. Property damages per accident class are also obtained from Parry (2004, Table 2), scaled by 0.27. Overall, we compute external costs from property damage at $0.04 billion.

Adding up the above components gives a total external cost of approximately $2 billion. Following de Palma and others (2008), Parry (2008), and the U.S. Federal Highway Administration (2000), we assume that the external accident cost per truck mile is 1.25 times that for a car mile. Thus, the average external cost per car mile is obtained by dividing the above total cost by car miles plus 1.25 times truck miles (from Table 1). This gives an average external cost per mile for cars and trucks of $0.06 and $0.07 respectively.

D. Road Damage and Noise

We measure road damage costs by central and local government spending on road maintenance in Chile, which totaled $0.85 billion in 2006.[32] We assume that all road maintenance expenditures in Santiago (21 percent of the total), and two-thirds in the rest of Chile, are due to vehicle driving (and that the remainder is due to weather, erosion, falling rocks, etc.). After allocating a portion of these costs to buses and cars, we are left with $0.08 per truck mile.[33]

[32] These figures were provided by David Noe and Rodrigo Terc from the Chilean Ministry of Finance. Implicitly, we assume that spending on road maintenance is optimal. If spending were sub-optimal, our calculation would understate road damage externalities, and vice versa if spending were excessive. However, there is little basis on which to adjust for this.

[33] Following Porter (1999), we assume the damage per truck mile is 1000 times the damage from a car or twice the damage from a bus mile, given that road damage is a rapidly escalating function of axle weight. The damage per

Vehicle noise costs have been estimated by examining how proximity to traffic affects local property values. For heavy trucks, THE U.S. FEDERAL HIGHWAY ADMINISTRATION (2000, Table 13) puts the (average) costs for urban and rural truck driving at $0.027 and $0.002 per mile, respectively. We multiply by the Chile/U.S. real income ratio (0.27) to transfer these values to Chile and weight by the share of mileage in urban and rural areas (0.87 and 0.13 respectively) to give a nationwide external cost of $0.006/mile.

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truck mile is given by solving for x, where $x(s_T + s_B/2 + s_C/1000)$ = (total damage cost)/(total vehicle miles), and s_T, s_B and s_C are the shares of truck, bus, and car miles in total vehicle miles (bus miles were 3.0 billion in 2006).

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