International fuel tax assessment: an application to Chile[*]

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APPENDIX

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Appendix A

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:

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

(A1)

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:

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

The government budget constraint, equating spending with fuel tax revenue, is $GOV = t_G G$.

Totally differentiating this constraint gives:

$$\frac{dGOV}{dt_G} = G + t_G \frac{dG}{dt_G} \tag{A3}$$

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

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

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

$$\frac{dG}{dt_G} = g\frac{dM}{dt_G} + M\frac{dg}{dt_G} \tag{A5}$$

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

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

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

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:

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

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

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

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:

$$u_T = \delta p_T \,, \qquad u_X = \delta p_X \tag{A9}$$

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

$$t_F + p_F = -k'(f) \tag{A10}$$

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:

$$u_{E_F} E_F' \frac{dF}{dt_F} + u_{E_T} E_T' \frac{dT}{dt_F} + \lambda \left\{ \frac{dGOV}{dt_F} - T \frac{dp_T}{dt_F} \right\} \tag{A11}$$

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

$$\frac{dGOV}{dt_F} = F + t_F \frac{dF}{dt_F} \tag{A12}$$

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

$$\frac{dp_T}{dt_F} = f \tag{A13}$$

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

Appendix B. Additional Details on External Cost Assessment

Pollution

For regions outside of Santiago: extrapolating from US estimates. There is reasonable consensus in the US 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\$). 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.).[2] NRC (2009) assumed a VSL of \$6 million (see also US 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 US estimates using the following, commonly used formula (e.g., Cifuentes *et al*., 2005, pp. 40-41):

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

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.[3]

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

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

[3] 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.

million.[4]

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 US rates (BTS, 2008, table 4.38).[5]

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

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 columns of the upper part of table B1.[6] The numbers here are based on both PM and ozone exposure, with basic morbidity and mortality estimates from a Chilean study (Cifuentes, 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 US evidence suggesting that the relationship between health impacts and pollution concentrations

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[4] Viscusi and Aldy (2003) and Miller (1997) 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., Hammitt *et al*., 2000; Cropper and Sahin, 2009). Our lower bound value is more in line with a local, stated preference study, after updating (Cifuentes *et al*., 2000).

[5] 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.

[6] 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 US literature.

is better represented by a concave (log-linear) rather than linear function (Pope *et al.*, 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).[7] 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.

Congestion

Average delay for Santiago. We obtain travel speeds for Santiago from the ESTRAUS model.[8] 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

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[7] 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.

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

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 the peak period and 50 percent at off-peak (including weekends) hence delay averaged over time of day is 0.009 hours per mile.[9]

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:

$$T = T_f\{1 + \alpha V^{\theta}\} \tag{C2}$$

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: 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

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

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; DOT, 1997; Mackie *et al*., 2003). Based on average urban wage rates in BLS (2006, table 1), this implies a US VOT of $10/hour.

To extrapolate to Chile, we multiply by the ratio of the Chilean to US 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 *et al*., 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.[10]

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.[11] 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

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[10] 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 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.

[11] Figures are from http://www.conaset.cl.

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.[12] 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/US VSL (0.27). These costs are $0.023 million, $0.005 million and

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[12] Again, see http://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, 2000).

$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 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 that is 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 *et al*. (2008), Parry (2008), and FHWA (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.

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.[13] 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.[14]

Vehicle noise costs have been estimated by examining how proximity to traffic affects local property values. For heavy trucks FHWA (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/US 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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[13] 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.

[14] 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 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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Table B1. Pollution Damage Calculations for Santiago

Health effect	Instances of health effect		cost per effect $ thousands
	Automobiles	Trucks	
Acute mortality	83	70	1,600
Long-term mortality	240	200	1,600
Hospital admissions	332	277	1.45
Emergency room admissions	3,377	2,814	0.18
Chronic bronchitis	515	429	52.7
Acute bronchitis	876	730	0.03
Asthma attacks	18,693	15,578	0.03
Work days lost	157,450	131,320	0.03
Restricted activity days and symptom days	538,010	448,230	0.01
Total health cost, $ million	556	463	
Materials damage, $million	85	73	
Total pollution cost, $million	641	536	
Fraction of cost due to mortality	0.81	0.80	
Pollution cost, US$/mile	0.06	0.19	

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