THE EXTERNAL COSTS OF PRIVATE VERSUS PUBLIC ROAD TRANSPORT IN THE METROPOLITAN AREA OF SANTIAGO, CHILE

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ABSTRACT

We estimate marginal external costs per driven kilometer in the Metropolitan Area of Santiago for car and bus. At peak times, the marginal external cost per kilometer for a petrol car is estimated at CLP 474 with a 90 percent confidence interval ranging from CLP 319 to CLP 631; almost the same values as for a diesel car. The marginal external cost for the bus is CLP 1,895, with an interval confidence ranging from CLP 1,170 to CLP 2,638. At off-peak times, all these values go down as congestion decreases significantly. The median externality cost for a petrol car is CLP 222 with a confidence interval ranging from CLP 124 to CLP 318 (almost same values for a diesel car). The median value for the bus is CLP 1,186 with an interval confidence from CLP 556 to CLP 1,809.

A most relevant comparison is the conversion of these figures to a marginal external cost per passenger-kilometer. When so doing, petrol cars, diesel cars and buses impose an external cost of CLP 380, CLP 389 and CLP 43 respectively at peak hour times. Travel by bus generates the lowest external costs, nine (9) times less than auto-travel. At off-peak hours, differences shrink to less than three times: marginal external cost are CLP 178, CLP 186 and CLP 70 for petrol car, diesel car and bus respectively.

Our estimates should contribute to a better debate on how to efficiently manage motor vehicles externalities by means of both (pigouvian) tax instruments, public transport subsidies and regulation, an ongoing debate in Metropolitan Santiago.

INTRODUCTION

Metropolitan urban transport produces several negatives externalities, among others, congestion, road crashes, air pollution, noise, spatial segregation. Drivers usually pay (fuel) taxes, but these are not necessarily designed to provide adequate incentives to internalize external effects. Hence, negative externalities are produced beyond their optimum level, negatively contributing to social welfare. The aim of this research is to shed light on the likely magnitudes of the marginal external costs of road transport in the Metropolitan Area of Santiago, the capital city of Chile. Estimating these marginal external costs should be a most relevant input for policy makers to device regulations and market instruments that contribute to a more sustainable urban transport.

To optimally manage the external costs of transport, we need to understand i) how user's equilibrium take place in urban transport markets, ii) how this equilibrium affects transport externalities and iii) how to monetize all these impacts. Having determined the external costs, pigouvian taxes could be set. With proper internalization, a new user's equilibrium would arise and externalities would be produced at their optimal level. For instance, Parry and Small (2005) show how to integrate different urban transport externalities in a microeconomic model that can determine the optimal fuel tax.

There exists a profuse literature dealing with these topics with contributions from both a theoretical and an empirical standpoint[1]. Regarding transport externalities among road users, the three most relevant externalities are travel delays brought about by congestion, road damage and accidents (Newbery 1994). The economics of travel delays have been studied since the nineteen-fifties: a very good review of different model of urban road congestion (from simple to complex treatments) is Small (1992) and Small and Verhoef (2007). Newbery (1988 and 1989) developed models to address road damage externalities. Vickrey (1968) was the first (up to our knowledge) to deal theoretically with road accident externalities. Many of these ideas were later formalized by Jansson (1994).

Other road externalities have been dealt with in a more piecemeal fashion: they include air pollution[2], greenhouse effects, noise, barrier effects, among others. In particular, air pollution has been extensively studied by epidemiologists who have shown that as air quality deteriorates, health outcomes worsen in terms of both mortality and morbidity (Pope and Dockery, 2006). As we know from national emission inventories (DICTUC, 2007) road transport is among the main polluters contributing to deteriorated air quality. Transport models that predict traffic flows and average speeds on network links could be used to estimate vehicles emissions of air pollutants (including CO2) and noise. Instead, barrier effects are one of the less well-studied environmental impacts associated with transport infrastructure. The time lost by pedestrians or vehicles for crossing infrastructure could be one very crude measure. More important, these barrier effects refer to the separation of people from facilities, services and social networks within a community, and/or people changing

[1] The economic literature abound with theoretical treatments of externalities and case studies of valuation of externalities. The review to be presented is by no means an extensive one. In our limited review, we tended to select some 'classical' books and/or material from transport-related handbooks when available.

[2] Newbery (1994) reckons air pollution as one of the most relevant transport externalities together with travel delays, road accidents and road damage.

travel patterns due to the physical or psychological barriers created by transport corridors and their use. Its valuation has been systematically ignored or underplayed in transport planning and environmental impact assessment.

Once the link between car usage and externalities is established, the next step in terms of economic analysis is their monetization. Basically, we need to have estimates of the value of travel time savings, the value of life and limb, the value of quietness, etc. As these hedonic goods are not sold in markets, there is a need to estimate them by means of statistical analyses. Freeman (1993, 2003) is a classical textbook in the valuation of non-market goods. Regarding the valuation of transport externalities, people must not only be aware of the externality impacts, but they must also have a clear understanding of its negative welfare effects and be able to express consistent preferences for trading them off against money or other goods. It appears reasonable to postulate that some local externalities, such as traffic congestion, noise, the risk to life and limb fall into this category since they affect people's welfare on a daily basis (Nash, 1997). Hensher and Button (2003), Ortúzar and Rizzi (2006) and De Palma et al. (2011) contain several studies designed for the valuation of many local transport externalities. The valuation of global externalities from peoples' preferences such as greenhouse effects, and thus CO_2 emissions, should be a much more difficult task. Whilst these effects are less clear, sometimes not perceived at all, consequently people are not able to express consistent preferences for their trade-off.. Nonetheless, efforts have been made to estimate the social costs of carbon from a bottom up perspective. For a review on the estimation the social cost of carbon refer to Tol (2009).

As to reviews of external costs of transport, we mention just a few. Maddison et al. (1996) deal extensible with the external costs of road transport in the UK and also present case studies from Sweden, North America and the Netherlands. The externalities that are analyzed are greenhouse effects, local air pollution, noise pollution, congestion, road damage and accident costs. They also provide a catalogue of estimates of external costs in the annex of the book. Delucchi (2003) reviews estimations of external costs of air pollution, climate change, noise and water pollution for the United States at the national level. Small and Verhoef (2007) compile empirical evidence on the external cost of road accidents and of two environmental externalities: local pollution and the greenhouse effect. Delucchi and McCubbin (2011) and Friedich and Quinet (2011) report estimates of external costs of transport for different modes for the United States and Europe respectively. The first article cover congestion, accident, air pollution, climate change, noise and water pollution and energy-security costs at the national level; the second article also considers landscape effects.

From our analysis, we conclude there is consensus on the plausibility of monetizing at least four urban road transport externalities: travel delays road, accidents, air pollution and noise. Also road damage is feasible to be monetized, albeit most of the revised material ignores it. These monetary values could then be used as input in cost-benefit analysis of transport projects, transport regulations and transport pricing.

In this research, we proceed to monetize the external impacts of travel delays road, accidents, air pollution and noise of car and bus usage for Metropolitan Santiago, Chile. We leave aside road damage because of data limitations. In this respect, our study is of a very similar nature to the one by Sen et al. (2010) who estimate the marginal external costs of road transport for

Delhi, India. Our estimates should contribute another piece of valuable information in the current debate on how to efficiently manage motor vehicles externalities by means of both (pigouvian) tax instruments, public transport subsidies and regulation in Metropolitan Santiago.

This article is organized as follows. The first section provides the economic basics of urban road externalities. The second, third, fourth and fifth sections deal with the externalities of congestion, road accidents, air pollution and noise, respectively. Section six presents a summary of results and a discussion of our findings.

1. BASIC ANALYTICAL FRAMEWORK

With the aid of Figure 1, we explain the basics of motor-vehicles urban externalities. Assuming there is a demand for road use, drivers will perceive the costs they incur when driving given by the average cost curve. This curve is monotonically increasing with flow and should be interpreted as generalized cost-averaged generalize cost[3]. This average cost curve comprises components related to perceived travel time, risk of accidents and out-of-pocket costs (including fuel taxes) by the driver. Because of externalities, the social marginal costs of motoring are higher. These externalities costs include two types of externalities: externalities internal to road users (travel delays and risk of accidents); and externalities external to road users that affect the whole population at large (air pollution, noise, barrier effect).

As each driver only takes into account the costs she incurs, road user equilibrium takes place at flow f^0, where private marginal benefits equal private average costs, thus producing a welfare loss equal to area ABD. In this equilibrium, the marginal external cost corresponds to segment AB. A road toll or pigouvian tax equal to segment FD would give rise to the social optimum flow, f^*[4].

The available information will only allow us to estimate the marginal external cost curve in the neighborhood of the current level of car usage; that is, it will only be possible to estimate the value of the segment AB. If we wanted to estimate the optimal pigouvian tax, we need to know both the elasticity of the demand curve and of the average / marginal cost curve throughout. If these elasticity values are not available, one can do a sensitivity analysis assuming a range of values transferred from studies carried out for other metropolitan areas.

For our empirical calculation, all key selected parameters are based on the best available evidence as well as on our expert's criterion. As these parameters are also subject to error, we will carry out a Monte Carlo simulation assuming independent distributions for several

[3] Small and Chu (2003) show how this curve is determined in terms of travel times and define it as a time-averaged travel time curve. Summing other costs than travel time, we end up with the generalized cost of travel, thus our interpretation of the curve.
[4] This is true as long as there is no other distortion in the economy; otherwise, the optimal charge may be higher or lower than the pigouvian tax.

key parameters. We take 1,000 draws from each distribution and compute total external marginal costs. We report as point estimates of each externality the average values of the 1,000 draws. We will also report in the discussion section, the median value and the 10^{th} and 90^{th} percentiles for the total marginal external cost[5]. From the median total external marginal cost, we take the values corresponding to each one of the externalities analyzed and report these values as our central median point estimates of each externality.

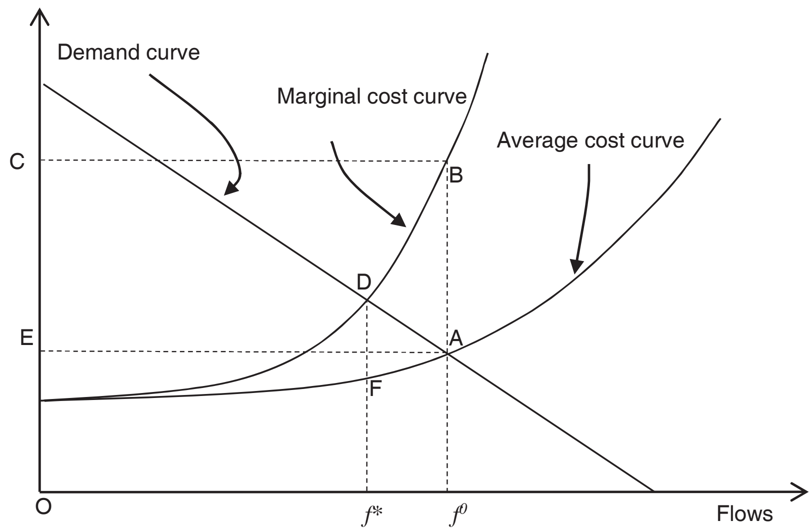

Figure 1: External costs of road motoring. If there is no road charge, market equilibrium corresponds to flow f^0, yielding a welfare loss equal to area ABD. If a road charge equal to segment FD is introduced, the social optimum flow f^* results.

2. CONGESTION

Congestion, measured as the increase in total travel times as a result of increasing traffic, only affects road users. Each driver only takes into account her costs of travelling and ignores the costs she imposes on other drivers when congestion develops. As all drivers are being delayed, marginal social costs are above personal average costs. The typical graph depicting the economic analysis of congestion is very much like Figure 1. For static economic analysis, we need a representation of congestion that relates time-averaged speed (or time-averaged travel time) to incoming flow (Small and Chu, 2005)[6].

There is a long tradition of analyzing urban transport projects in Chile. A four-step classical transport model has been calibrated for every major city and Santiago is no exception. These models are calibrated using data from travel surveys and vehicle and passenger counts and

[5] By total marginal external cost, we mean the sum of each marginal external cost.
[6] Incoming flow could be interpreted as vehicle-trips that are starting within a period.

are updated on average every ten years. The model for Santiago has two components. The first component is a trip generation model to forecast trip generation and trip attraction. The second component is a simultaneous transport equilibrium model ESTRAUS that performs the steps of trip distribution, modal split and trip assignment. This model was last calibrated for the City of Santiago for a morning peak hour and a non-peak representative hour corresponding to year 2001 (Fernández & De Cea Ingenieros, 2005). The road network comprises 8600 links, classified in five categories. Link costs are represented by a typical BPR-type function (Small and Verhoef, 2007, page 76, equation 3.9) according to its characteristics:

$$t_a = t_a^0\left(1+\alpha\left(\frac{f_a}{k_a}\right)^{\beta}\right),$$

where t_a: travel time on link a, t_a^0 free-flow travel time; *fa*: flow on link *a*, *ka*: link *a* capacity and α and β ($\beta > 1$) parameters to be calibrated.

Using the BPR functions calibrated for Santiago (Fernández & De Cea Ingenieros, 2005) and the outcome of ESTRAUS traffic assignments for the year 2010, marginal travel times and average travel times are computed for each network link. The external marginal travel time is obtained by subtracting average travel times from marginal travel times; this value is then multiplied by the number of vehicles and their occupancy rates and by the value of time and averaged across all network links. Results are available for a peak hour and a non-peak hour. Table 1 provides the most relevant information for our computations. The most disputable figure is the subjective value of travel time savings. We considered as our central value (CLP 1,740) a weighted average of the values of travel times per mode (car and bus) used in the ESTRAUS modal split module for Santiago the Chile. We also consider a minimum and a maximum value for the Monte Carlo analysis.

There is one important qualification regarding Table 1. There are two main type of buses operating in Santiago, rigid buses and articulated buses. In terms of ESTRAUS, articulated buses are equivalent to two rigid buses, with full occupancy doubling. We will only report values for rigid buses. In the last section, we return to this point.

Table 1. Congestion externalities: Relevant parameters

Parameter	**Value**
Value of time (2013 CLP/hour)	Triangular distribution 900; 1740; 3600
Occupancy rate: light vehicles	1.25 pax*
Occupancy rate – peak hours: buses	44 pax*
Occupancy rate – off-peak hours: buses	17 pax*
Equivalent vehicles: light vehicles	1
Equivalent vehicles: buses	2.5

*pax: passengers.

Marginal external costs point estimates per driven kilometer for peak hours are CLP 311 and CLP 857 for car and bus respectively. Marginal congestion costs in terms of driven kilometer for off-peak hours fall significantly to CLP 65 and CLP 186[7].

3. ROAD CRASHES

As an externality, road crashes mainly affect road users, and to a lesser extent the rest of society through property damages, police and firemen expenses, health services and insurance companies administrative costs. There exists an externality among road users if, as traffic flows vary, the risk of a crash also varies. The basic idea of road accidents externalities are given by this simple model based on Jansson (1994). Assume that accidents per unit of time (Acc) are given by a function such as $Acc = \alpha V^{\beta}$, with V flow (vehicles / unit of time). In this simply representation β is the elasticity of accidents with respect to flow. If β is greater than one, accidents rise more than flow as flow increases whereas if β is less than one, accidents increase at a lesser rate than flow. If β equals one, then accidents are proportional to flow so that risk remains the same. Hence we have for each case regarding the value of β, negative externalities, positive externalities or no externalities at all.

If there are heterogeneous traffic flows, say light vehicles (L) and heavy vehicles (H), then $Acc(L, H) = \kappa L^{\gamma} H^{\delta}$. In terms of risk (r), there are two functions for light vehicles and heavy vehicles respectively: $r(L) = \kappa L^{\gamma-1} H^{\delta}$ and $r(H) = \kappa L^{\gamma} H^{\delta-1}$. There are four relevant elasticities of accident risk: i) elasticity of risk for light vehicles with respect to light vehicles flow (γ-1), ii) elasticity of risk for light vehicles with respect to heavy vehicles flow (δ), iii) elasticity of risk for heavy vehicles with respect to light vehicles flow (γ), and iv) elasticity of risk for heavy vehicles with respect to heavy vehicles flow (δ-1). For instance, if both δ and γ equaled 1, there would be negative cross-externalities between flows, and no externalities within flows.

The empirical evidence is not conclusive regarding the above elasticities, but some assumptions are usually made. For interurban homogeneous flows, the risk of crashes is constant, that is, independent of traffic flows (Lindberg, 2001) and no externality among drivers exists; there are only external effects in terms of impacts on non-drivers. For homogenous urban transport flows, the risk of accidents grows with the flow (SNRA, 1989), but the seriousness diminishes[8] (Fridstrøm et al., 1995 y Fridstrøm, 1999). On the other hand, for heterogeneous traffic flows, heavy vehicles usually result unscathed from collisions with light vehicles, being the latter the party to suffer the consequences of the crash (Lindberg, 2001). Thus, the costs of crashes fall on the weak category. External costs generated by heavy vehicles depend on the elasticity of risk crashes between different traffic categories with respect to a change in the flow of heavy vehicles, E_{heavy}. The external costs from light vehicles are related to the elasticity of risk crashes between different traffic categories with respect to

[7] The output of ESTRAUS for off-peak hours for 2010 yields unlikely low levels of congestion. Thus to calculate the external cost of congestion for 2010, we apply the same relationship between peak and off-peak hours external costs produced by ESTRAUS for year 2001.
[8] This would be a positive externality from congestion.

a change in the flow of lighter vehicles, E_{light}, and to the amount of external costs imposed on non-driver agents. Limited empirical evidence suggests that E_{heavy} is greater than zero and E_{light} less than zero (Lindberg, 2001). This way, road users from the light vehicle category should be compensated; this last phenomenon could be interpreted as safety in the numbers.

Alcoholado (2006) and Alcoholado and Rizzi (2008) estimated urban and interurban marginal external costs for each type of vehicle for every region of the country. For each region of the country, Carabineros de Chile reports all accidents with fatal injuries, severe injuries, light injuries and no-health damage. The National Institute of Statistics provides the number of motor vehicles per type-category for every region of the country. Using information from different sources, Alcoholado (2006) and Alcoholado and Rizzi (2008) also elaborated a measure of driven kilometers per type of vehicle for each region of the country. Their model considers accidents according to their health and the number of vehicles of different categories involved. The types of vehicles considered were light vehicles, buses, commercial vehicles, taxis, motorcycles and heavy vehicles. Pedestrians and cyclist were treated as two different categories of road users. With all this information for the years 2000 to 2003, they estimated the own-flow and cross-flow elasticities required to compute external costs.

The other key parameter in these calculations is the value of life and limb, the most critical value being the one regarding mortality prevention also known as the value of a statistical life (VVE). Both scarce Chilean evidence and ample international evidence suggest a multiplicity of values. Deciding on any such value or a range of values to apply to our study will require a great deal of faith. Instead, we follow a more theoretical approach (that is also subject to debate). In very simple model of the type postulated by Jones Lee (1994), the VVE equals lifetime income divided by the elasticity of utility with respect to income. We approximate lifetime income by the capital human approach as calculated in Chile by the Ministerio de Desarrollo Social. We also assume that the elasticity value distributes uniformly between 0.08 and 0.8. Thus, our estimates of the VVE range uniformly from 3,916.3UF[9] to 39,162.5UF. Following usual practice, we assume that the value of avoiding a serious injury casualty and a light injury casualty are valued at 20 percent and one percent respectively. Our estimation of marginal external costs point estimates of road crashes per driven kilometer are set at CLP 132 and CLP 739 for car and bus respectively.

4. AIR POLLUTION COSTS

Motor vehicles emit pollutants that contribute to air pollution. Currently, the Metropolitan Area of Santiago imposes stringent restrictions to motor vehicle use and other emission sources such industrial processes or residential heating. Because of poor ventilation conditions from May to August, air quality could worsen during this period and additional restrictions on motor vehicle use are established. Deteriorated air quality affects health,

[9] The UF is a unit account monthly adjusted according the consumer price index. For 30th June, 1UF = CLP 22,852.67.

reduces visibility and CO2 emissions contributes to climate change[10]. We estimate the impact of motorized vehicles in terms of these negative effects separately.

4.1 Health effects

Health effects of pollutants are estimated using exponential functions that link health risks to ambient concentrations of PM2.5 and O3 (Cifuentes, Borja-Aburto et al. 2001). Typically, an exponential relationship between concentrations and health effects is assumed, of the following type

$$H_{jp} = B_j \exp\left(\beta_{jp} C_p\right) P_{jp} \tag{1}$$

H_{pj}: health effect j for ambient concentrations of pollutant p;
β_{pj}: concentration-response risk coefficient for health effect j per unit of pollutant p;
C_p: ambient concentration level of pollutant p;
B_j: baseline incidence rate for health effect j;
P_{jp}: population exposed to health effect j for pollutant p.

Changes in concentration levels thus prompt changes in health effects. Thus for a ΔC change in concentration levels from level 0 to level 1, there will be ΔH changes in the health effects as

$$\Delta H_{jp} = B_j \left(\exp\left(\beta_{jp} C_p^1\right) - \exp\left(\beta_{jp} C_p^0\right)\right) P_{jp} = B_j \left(\exp\left(\beta_{jp} \Delta C_p\right) - 1\right) P_{jp}$$

If we linearize the above function, we get

$$\Delta H_{jp} = B_j \left(\exp\left(\beta_{jp} \Delta C_p\right) - 1\right) P_{jp} \approx B_j \beta_{jp} \Delta C_p P_{jp} \tag{2}$$

To estimate the impact of transport emissions, we also need to establish a relationship between changes in emissions of precursor pollutants and changes in concentration levels of MP2.5 and O3. We will refer to this relationship as emission-concentration factors. Thus, we will assume the following linear relationship using a simple roll back model (Chang and Winstock, 1975).

$$FEC_i^p = \frac{\partial C_p}{\partial E_i} \approx \frac{\Delta C_p}{\Delta E_i} \tag{3}$$

FEC_i^p: the relationship between emissions of pollutant i and ambient concentrations of pollutant p;
C^p: ambient concentration of pollutant p;

[10] There is no good quality local data to estimate agricultural losses and damages to building facades. According to the international evidence, though, these effects are a small part of total external costs.

E_i: emissions of precursor pollutant i.

Both linear assumptions have been made before by Small and Kazini (1995) and they are implicit in many studies. Small and Kazini provide a plausible explanation to justify the linearity assumptions based on some empirical evidence[11].

If we multiply equation (2) and equation (3), we can estimate the number of changes in health effects following changes in emissions of precursor pollutants (ΔE) by means of equation (4):

$$\frac{\Delta H_{ji}}{\Delta E_i} = \Delta H_{jp} FEC_i^p \tag{4}$$

Multiplying equation (4) by the money value assigned to preventing/increasing a healths effect in one unit provides the total money value of reducing/increasing emisions of precursor pollutant i, a figure expressed as USD/Ton of pollutant p. We can still go one step further to obtain a money value in terms of vehicle-kilometres. Emissions of precursor pollutants depend on the type of vehicle and speed of circulation. The COPERT model provides with these emission factors. Hence, by multiplying both sides of equation (4) by vehicle emission factors (10^{-6}Ton/km), we arrive to a figure expressed as CLP/km. Based on ESTRAUS outputs, we assumed that speed follows a gamma distribution with mean and variance 44 km/hr and 50 km/hr; and 24 km/hr and 42 km/hr for car and bus respectevely.

We now describe the data used to perform all the steps described above to arrive to marginal external costs per vehicle kilometer. Table 2[12] shows the health endpoints to be appraised, the age of the people affected by each endpoint and the beta coefficients (β) associated with unit increases in the concentrations of pollutants PM2.5 and O3. For PM2.5, the relevant figure is a unit increase in $\mu g/m^3$ in the annual average of hourly concentration values; for O_3, a unit increase in $\mu g/m^3$ in the annual average of hourly daily maximum concentration values. As there is no local evidence about the values of the beta coefficients[13], these were taken from the international literature. The source of each relative risk coefficient is reported in the table. For the Monte Carlo risk analysis, it is assumed that all these values are Normally distributed with mean and standard deviation as reported in Table 2. Table 3 shows the incidence rate for each health endpoints and affected population. Incidence rates were computed from hospital records from the Chilean Ministry of Health Department of Health Statistics[14] and are assumed to be exact.

TABLE 2

TABLE 3

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[11] One counterexample is McCubin and Deluchi (1999), who assume a non-linear relationship between emissions and concentrations in their modelling for estimating the health costs of motor-vehicle related air pollution.
[12] All tables are shown at the end of the paper.
[13] Cifuentes et al. (2001) estimate the relative risk coefficient for the impact of PM2.5 on all mortality using longitudinal data from Santiago. New epidemiological studies show, however, that longitudinal studies underestimate the true mortality effects.
[14] http://deis.minsal.cl/index.asp

The monetary benefits per health event reduced are given in Table 4. All monetary values are assumed to be Triangular distributed, except for the value of a statistical life as discussed in section 3. All relevant parameters are available in Table 4.

TABLE 4

Table 5 shows total emissions of primary pollutants, the amount that corresponds to mobile sources, the proportion (and levels) of $PM_{2.5}$ and O_3 concentrations attributable to each precursor pollutant emitted by mobile sources and the emissions-concentration factors calculated as explained in the table. Under simplifying assumptions, filter analysis provided information that permits to trace up to 95 percent of concentrations of $PM_{2.5}$ to primary and secondary pollutants emission. Further, if O_3 formation in the Santiago Metropolitan Area is assumed to be 'NOX limited' we can trace NO_x emission to O_3 ambient concentrations. Given that the ratio of emissions of VOC to NO_x is almost two, the cost per additional ton of NO_x will be almost twice the cost per additional ton of VOC. Thus, reductions in emissions of NOX could be quite cost-effective. There are several air-quality monitoring stations that provide the information to build the required air quality indexes[15].

TABLE 5

Marginal external costs point estimates of emissions of precursors of PM2.5 per driven kilometer are CLP 14, CLP 26 and CLP 193 for petrol car, diesel car and bus respectively. The respective values for marginal external costs in terms of emissions of precursors of O3 are estimated at CLP6, CLP5 and CLP 43.

4.2 Visibility

Visibility is interpreted as visual range measured in kilometers. Sanchez et al (1999) estimated hourly visibility levels as a function of PM10 concentration levels, relative humidity and temperature. In DICTUC (2007), daily visibility is then computed as the average hourly visibility. If daily visibility was above 12km, the day is considered to be of high visibility, otherwise it is a day of low visibility. Approximately, there are 80 days a year of high visibility in the city of Santiago. The model permits to estimate the marginal impact of an increase of one $\mu g/m^3$ of annual daily average PM10 on visibility. An extra unit of PM10 reduces approximately 2 days a year of high visibility. Rizzi et al. (2014) estimate households' willingness to pay (WTP) for improved visibility. In their survey, days were classified as of low visibility or high visibility. Households' willingness to pay for an extra day of high visibility was estimated and when aggregated across all households, in their most conservative model an extra day of high visibility was valued at 7,736 UF, with lower and upper bounds between 110 UF and 12,086 UF.

[15] This link (in Spanish) provides on-time hourly information on concentration levels for several pollutants http://www.seremisaludrm.cl/sitio/pag/aire/indexjs3aireindices-prueba.asp.

Following an analogous process to that described in section 2.2 we assigned emissions of precursor pollutants of PM10 to estimate marginal external costs per vehicle kilometer in terms of visibility impacts. This result is negligible when converted to CLP per kilometer.

4.3 CO_2 costs

To estimate the external cost attributable to CO_2 emissions from mobile sources, we make simple calculations. From IPCC (2006)[16], CO_2 emissions of diesel and petrol are 3,216 Kg CO_2/Ton and 3,083 Kg CO_2/Ton, respectively. Analogous to health effects, we assume that fuel efficiency depends on the type of vehicle and speed of circulation. We based our calculations on COPERT model fuel efficiency factors.

To asses external costs we use observed market prices[17]. Following MDS (2011) a proxy for the social cost of carbon was based on the average market price of emission reduction credits (ERCs) under the Clean Development Mechanism published in www.eex.com. ERCs correspond to offsets polluters can purchase in order to neutralize their contribution to climate change. Carbon emissions will thus be balanced out by funding projects which cause an equal reduction in emissions elsewhere.

Under this method, MDS (2011) offers a value of USD 5 per ton of CO_2. To account for future uncertainty in market price, CO_2 monetary values are assumed to be Triangular distributed with mode the value proposed by MDS (2011) and minimum and maximum values observed historical transaction values[18], of USD 0 and USD 20 per Ton of CO_2. Marginal external costs point estimates of emissions of CO2.5 per kilometer are estimated at CLP 1, CLP 1 and CLP 5 for petrol car, diesel car and bus respectively.

5. NOISE

In Metropolitan Santiago, noise pollution is basically created by motor vehicles. According to MMA (2012), most households are exposed to level of noise considered not apt for residential aptitude. Exposure to excessive noise produces psychological effects (mental stress, irritableness), hearing effects (deafness, temporal and permanent displacement of hearing thresholds) and non-hearing health effects as heightened risk of cardiovascular and circulatory disorders. Noise is also a source of productivity losses.

To quantify all these effects is a major task, as most individuals do not understand all the consequences of noise pollution on their welfare. Because of these difficulties, noise will be monetized based on a residential aptitude criterion as the welfare loss that households suffer from noise exposure at home. This value is given by the household WTP to reduce noise

[16] 2006 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html
[17] http://www.sendeco2.com (08-09-2012)
[18] http://www.carboncatalog.org/providers/standard-carbon/ (12/03/2012)

exposure and thus it neglects WTP to reduce noise exposure at other places. It also neglects external costs in terms of health effects[19] and others such as potential damages to buildings through ambient vibrations attributable to noise.

Noise externalities are estimated using the modeling approach proposed by DICTUC (2007). DICTUC (2007), estimates sidewalk total static sound pressure (Lw_a) for each link of the network with length l_a based on ESTRAUS calculations of traffic flows on peak and off-peak periods, and noise emission factors dependent on speed of circulation (FE_{ij}) for vehicle type i. Daily emissions are computed extrapolating peak and off-peak flow estimations to the remaining hours of the day.

Assuming that the welfare loss is associated with household exposition, static sound pressure estimations must be attenuated as follows:

$$Leq_a = Lw_a + D_c - A_{Div} - A_{Bar}$$
(4)

Where, Leq_a is the continuous noise pressures level for link a, Lw_a is the static sound pressure for link a, D_c is a directivity correction factor, A_{Div} is a distance attenuation factor and A_{Bar} is barrier attenuation factor as reported in DICTUC (2007).

Our selected measure of noise exposure corresponds LeqDN, a noise day and night average index[20] that provides a reasonable indicator of how much a household is affected by noise externalities:

$$\mathrm{LeqDN}_a = 10 \times Log\left[\frac{1}{15}\sum_7^{22} 10^{\frac{\mathrm{Leq}_a}{10}} + \frac{1}{9}\sum_{22}^{7} 10^{\frac{\mathrm{Leq}_a+10}{10}}\right]$$

where $\boldsymbol{Leq_j}$ is the noise pressure at hour h on link a. The unit of measure of this indicator is the decibel, dB (A).

Households' WTP per unit of dB(A) reduction per month was estimated by Galilea and Ortúzar (2005). As their survey consisted of middle income and high income households, we select the lower value of their confidence interval for model ML-1 as the relevant WTP figure, amounting to CLP 1.900 per dB(A) per month. An additional and debatable assumption is made: at the margin all dB(A) reductions are worth the same amount of money[21]. Unfortunately, there is no information to monetize this value according to exposure at the margin. Estimated marginal external costs point estimates of noise per driven kilometer are CLP3 and CLP30 for car and bus respectively.

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[19] If people were able to clearly identify the consequences of noise pollution on their health, their WTP would take those effects into account. However, this is quite unlikely to be the case.
[20] Day hours go from 7.00 to 22.00 and night hours, from 22.00 to 7.00.
[21] Noise exposure is a highly local phenomenon. Our assumption implies that marginal WTP for noise reduction for two households located in different places, at current exposure levels, is the same even if noise exposure differs.

6. TOTAL MARGINAL EXTERNAL COSTS AND A DISCUSSION

Table 6 shows marginal external costs point estimates per driven kilometer for the Santiago Metropolitan Area and its interval confidence given by the 10^{th} and 90^{th} percentile, for both car and bus, peak and off-peak hours. At peak times, the average value for petrol cars is CLP 474 with a confidence interval ranging from 319 to 631; almost the same values as for diesel cars. The average value for the bus is CLP 1895, with an interval confidence from CLP 1,170 to CLP 2,638. For articulated buses, the values will be the double than those for standard rigid buses. Congestion is the externality with the largest effect followed by accidents and, farther behind air pollution-related health effects[22]. CO2, visibility effects and noise are too low to have an impact. Road noise seems not to be a serious problem in terms of welfare losses, a debatable conclusion in the light of persistent high levels of noise in the city.

TABLE 6

At off-peak times, the median externality cost per driven kilometer for petrol car is CLP 222 with a confidence interval ranging from CLP 124 to CLP 318; almost the same values as for diesel cars. The median value for the bus is CLP 1,186, with an interval confidence from CLP 556 to CLP 1,809. Congestion is now much less severe and accident externalities dominate. For all externalities except congestion, the estimated values do not discriminate between peak and off-peak hours. In Metropolitan Santiago, congestion is still a localized externality in terms of time of day, suggesting that road pricing, if implemented, should be established at peak hours.

To put the above results in real-life perspective, consider the petrol tax, the only tax related to intensity of use. The value of this tax when translated to a charge per driven km amounts to around CLP 24, CLP 6 and CLP 20 for petrol car, diesel car and a bus respectively. Drivers do pay many other taxes related to car possession but not related to car usage. These taxes include an ad valorem tax, an added value tax, the driving permit and compulsory bodily damages insurance. The total revenue they generate, though, is much lower than revenues collected by fuel taxes (around 50 percent). Incentives are not conducive to efficient marginal decisions by car drivers; and a second-best argument would justify an otherwise low diesel tax for buses. As another reference point, cars and buses pay CLP 168 and CLP 336 per kilometer on tolled highways in Metropolitan Santiago at peak times. Once again these values are lower than marginal external costs at peak times but higher than fuel taxes. These tolls, however, are set as to allow a financial viable private operation of highways (including the recovery of capital costs); they are not set to internalize motor vehicles externalities.

A most relevant comparison is the conversion of these figures to a marginal external median cost per passenger-kilometer. When so doing, petrol cars, diesel cars and buses impose an external cost (at average values) of CLP 380, CLP 389 and CLP 43 respectively at peak hour

[22] There are a few day per year when air quality greatly deteriorates and additional restrictions on car usage applies. Our calculations of external marginal costs in terms of pollution-related health effects are based on daily annual averages that smooth out these few days of high levels of concentration of pollutants. As shown by Baumol and Oates (1988), pricing is not a good tool to deal with extreme events; regulation is better as it is currently done in Santiago.

times[23]. Travel by bus generates the lowest external costs, nine (9) times less than auto-travel. At off-peak hours, differences shrink to three times: marginal external median cost are at CLP 178, CLP 186 and CLP 70 for petrol car, diesel car and bus respectively. Externalities per passenger kilometers are higher for buses at off-peak hour than at peak-hours: at off-peak times bus occupancy rates fall sharply.

We close this article with two comparisons. First, we compare our values with those estimated by Parry and Strand (2001) for Chile. They estimate what the optimal petrol tax should be for Chile. This estimate is based on assumptions they made about the average marginal external costs of transport for different regions of the country. Most of their estimates are based on values transferred from the USA, leaving aside the relative rich amount of local data. So we also estimated the external marginal costs of transport for car and bus for Metropolitan Santiago assuming their i) delay for congested areas for both peak and off-peak hours (minutes per kilometer), ii) value of travel time savings (CLP per hour), iii) value of statistical life (CLP per premature mortality) instead of ours. This way we can make a crude comparison of our values against theirs[24]. Table 7 report marginal external costs per driven kilometer for both car and bus.

TABLE 7

Two striking differences between Parry and Strand (2011) and our estimates stand out: congestion and accidents. According to their values, congestion seems to be a mild external cost of road transport in Santiago, especially at peak hours. This striking difference is mainly due to the fact they consider an extra car-kilometer at peak times generates an externality of 1.8 minutes based on a very crude assumption of speed-flow curves for Santiago, assuming a BPR function with parameters $\alpha = 0.15$ and $\beta = 4$ and a occupancy rates of one (1) person per vehicle. Our value was retrieved from the ESTRAUS model output: the congestion external cost is 8.8 minutes per driven kilometer, with an implicit occupancy rate of 2.4 persons per vehicle (a weighted average of car and bus occupancy rates). Regarding accidents, their values are much higher than ours. This difference is due to Parry and Strand assuming a much higher figure for the value of statistical life: they simply transfer the USA value and adjust it by income and by the elasticity of willingness to pay for safety with respect to income. This also affects the impacts in terms of health effects of air pollution but to a lesser extent. In our opinion, Parry and Strand did a poor job at understanding congestion for Metropolitan Santiago; regarding the value of statistical life there is less room to criticize their approach. When comparing values for cars, ours are relatively higher for peak hours, while the reverse occurs for non-peak hours. For buses, their values are slightly higher than ours for peak hours and around two times higher than ours for off-peak hours.

As a second comparison, we compare our values to those estimated for other metropolitan areas. The literature tends to report values that are national averages at both the urban and rural level. A comparison of these values with our values will be of very little help. Instead, we will compare our values to point estimates of marginal external cost per kilometer for the

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[23] Assuming that the marginal externality cost of a driven kilometer of an articulated bus is the double of the cost of a standard rigid bus and that occupancy also doubles, the cost per passenger-kilometer remains the same.

[24] Our comparison ignores external costs in terms of noise and visibility. Regarding noise they just transfer a value for trucks from the USA; and they not consider visibility an almost negligible externality.

city of Delhi (Sen et al, 2010). For their calculations, these authors transfer most of the relevant parameters whereas in our case we have at our disposal more local information. For petrol cars, they estimate externalities at CLP 89 and CLP 12 for peak and off-peak hours respectively; and at CLP 438 and CLP 285 for buses respectively. These values are much lower than our median values, especially regarding petrol cars. However, when taking into account that per capita income in Chile at purchasing power parity is four times that of India, these values are roughly similar.

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\TABLES

Table 2

Beta Coeficients (PM2.5)

Normally Distributed with	Mean (age group)					Standard Deviation (age group)					
Endpoint	**<18**	**18-29**	**30-64**	**65+**	**All**	**<18**	**18-29**	**30-64**	**65+**	**All**	**Source**
Premature Mortality (Cohort)			0,93%	0,93%				0,29%	0,29%		Pope et al (2004)
HA - Cardiovascular Disease		0,15%	0,15%	0,16%			0,04%	0,04%	0,03%		Moolgavkar (2000)[2,3] and Moolgavkar (2003)[4]
HA - Respiratory Disease											
HA - COPD		0,24%	0,24%	0,12%			0,08%	0,08%	0,21%		Moolgavkar (2000)[2,3] and Ito (2003)[4]
HA - Pneumonia				0,40%					0,17%		Ito (2003)
HA - Asthma	0,33%	0,33%	0,33%			0,10%	0,10%	0,10%			Sheppard (2003)
ERV - Asthma	1,65%					0,41%					Norris et al (2003)
Work Loss Days (WLDs)		0,46%	0,46%				0,04%	0,04%			Ostro (1987)
Restricted Activity Days (RADs)		0,48%	0,48%				0,03%	0,03%			Ostro (1987)

Age group: [1] <18, [2] 18-29, [3] 30-64 y [4] 65+.

Beta Coeficients (O3)

Normally Distributed with	Mid (age group)					Stdr (age group)					
Endpoint	**<18**	**18-29**	**30-64**	**65+**	**All**	**<18**	**18-29**	**30-64**	**65+**	**All**	**Source**
Premature Mortality (Time Series)					0,15%					0,04%	Bell et al (2005)
HA - Cardiovascular Disease											
HA - Respiratory Disease				0,27%					0,14%		Schwartz (1995)
HA - COPD											
HA - Pneumonia											
HA - Asthma											
ERV - Asthma					0,09%					0,1%	Peel et al (2005)
Work Loss Days (WLDs)											Bell et al (2005)
Restricted Activity Days (RADs)											

Age group: [1] <18, [2] 18-29, [3] 30-64 y [4] 65+.

Table 3

Incidence Rate (Cases/(1xe^5 inhabitants))

Endpoint	**<18**	**18-29**	**30-64**	**65+**
Premature Mortality (Pope et al (2004))	3	5	74	2.015
Premature Mortality (Bell et al (2005))	47	27	247	4.366
HA - Cardiovascular Disease	24	40	398	2.605
HA - Respiratory Disease	1.629	214	283	1.920
HA - COPD	649	32	94	1.022
HA - Pneumonia	189	5	35	427
HA - Asthma	39	5	12	39
ERV - Asthma	0	0	0	0
Work Loss Days (WLDs)	0	165.320	153.164	0
Restricted Activity Days (RADs)	0	646.050	646.050	0
Total population (100,000)	19	13	29	6

Table 4

Monetary values (UF/case)	Mid (age group)					
Endpoint	**<18**	**18-29**	**30-64**	**65+**	**All**	**Source**
Premature Mortality (VSL)-case	*Same values as those reported in section X*					Iraguen y Ortuzar (2004)
HA - Cardiovascular Disease		45	45	44		DICTUC (2012)
HA - Respiratory Disease	18	24	24	29		DICTUC (2012)
HA - COPD					27	DICTUC (2012)
HA - Pneumonia					29	DICTUC (2012)
HA - Asthma	21	21	21	23		DICTUC (2012)
ERV - Asthma					1	DICTUC (2012)
Work Loss Days (WLDs)	0	0,7	0,7	0		DICTUC (2012)
Restricted Activity Days (RADs)		0,2	0,2			DICTUC (2012)

HA: Hospital Admissions/ERV: Emergency Room Visits

**CER - 01-2008/07-2012

Triangular (min, mid, max)

Table 5. From emissions of precursor pollutants to contaminants concentrations

Primary pollutants	Emissions [Ton/year]		Concentration [$\mu g/m^3$ annual average]						Emission-Concentration factors FEC [$\mu g/m^3$/ton]		
	Total	Mobile Sources	% $PM_{2.5}$	Total $PM_{2.5}$	% PM_{10}	Total PM_{10}	% O_3	Total O_3	$PM_{2.5}$	PM_{10}	O_3
	A[1]	B[2]	C1 [3]	D1	C2 [3]	D2	C3 [3]	D3	E1 = D1 / A	E2 = D2 / A	E3 = D3 / A
$PM_{2.5}$	2,771	334	50%	15					5.4E-03		
$PM_{2.5sd}$	436	296	3%	1					8.1E-04		
PM_{10}	3,274	337			29%	17				5.3E-03	
PM_{10sd}	3,883	2,065			13%	8				9.1E-04	
SO_2	13,206	59	6%	2	4%	2			1.4E-04	1.8E-04	
COV	84,924	1,984					50%	10			1.1E-04
NO_X	25,175	11,359	26%	8	8%	5	50%	10	1.9E-04	1.2E-04	3.1E-04
NH_3	32,023	198	10%	3	7%	4			9.2E-05	1.3E-04	
TOTAL			95%	30	61%	60	100%	20			

Source: [1] Data from emissions inventories; [2] Data modeled form emission factors; [3] Element concentration data from filter analysis: Sulfate (SO_2), Nitrate (NO_X), Ammonium (NH_3), Elemental and Organic Carbon (PM), Natural Dust (PM_{sd}); [4] Annual average concentration levels for 2005; sd: Suspended Dust.

Table 6. Marginal external costs per kilometer (CLP 2013)

PEAK	Congestion	Accidents	PM2.5	O3	CO2	Visibility	Noise	Mean	10th percentile	90th percentile
Passenger Car (PC) - Petrol (<2.5 t)	319	132	14	6	1	0	3	474	319	631
Passenger Car (PC) - Diesel (<2.5 t)	319	132	26	5	1	0	3	486	326	648
Urban Bus - Rigid	879	739	193	47	5	1	30	1,895	1,170	2,638
OFF-PEAK	Congestion	Accidents	PM2.5	O3	CO2	Visibility	Noise	Mean	10th percentile	90th percentile
Passenger Car (PC) - Petrol (<2.5 t)	67	132	14	6	1	0	3	222	124	318
Passenger Car (PC) - Diesel (<2.5 t)	67	132	26	5	1	0	3	233	127	338
Urban Bus - Rigid	191	739	177	43	5	1	30	1,186	556	1,809

Table 7. Marginal external costs per kilometer (CLP 2013) according to Parry & Strand (2011).

PEAK	Congestion	Accidents	PM2.5	O3	CO2	Visibility	Noise	Median	10th percentile	90th percentile
Passenger Car (PC) - Petrol (<2.5 t)	54	274	27	11	2	0	0	368	274	496
Passenger Car (PC) - Diesel (<2.5 t)	54	274	51	9	2	0	0	390	288	537
Urban Bus - Rigid	149	1,535	285	79	16	0	0	2,064	1,489	3,068
OFF-PEAK	Congestion	Accidents	PM2.5	O3	CO2	Visibility	Noise	Median	10th percentile	90th percentile
Passenger Car (PC) - Petrol (<2.5 t)	26	274	27	11	2	0	0	340	244	471
Passenger Car (PC) - Diesel (<2.5 t)	26	274	50	9	2	0	0	361	258	506
Urban Bus - Rigid	73	1,535	263	74	15	0	0	1,959	1,416	2,947