DISCUSSION PAPER

June 2008 ■ RFF DP 08-17

How Should Passenger Travel in Mexico City Be Priced?

Ian W.H. Parry and Govinda R. Timilsina

1616 P St. NW
Washington, DC 20036
202-328-5000 www.rff.org

RESOURCES FOR THE FUTURE

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Abstract

This paper uses an analytical-simulation model to examine the optimal extent and welfare effects of pricing reforms for passenger transportation in Mexico City. The model incorporates travel by auto, microbus, public bus, and rail, plus externalities from local and global air pollution, traffic congestion, and road accidents. In our benchmark case, the optimal gasoline tax is $2.72 (29.6 pesos) per gallon, or 16 times the current tax. However, a per-mile toll would reduce traffic congestion, the largest externality, more directly, and we put the optimized auto toll at 20.3 cents per mile. Tolls should also be imposed on microbuses even though the welfare gains are relatively modest, as are those from reforming public transit fares.

Key Words: gasoline taxes, mileage tolls, transit subsidy, pollution, congestion, Mexico City, welfare effects

JEL Classification Numbers: R48, H21, H23

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1. Introduction

The Mexico City metropolitan area is ranked among the most polluted cities in the world and is also one of the most congested in terms of lowest average speed of passenger vehicles (Table 1). Air pollution is responsible for an estimated 4,000 premature deaths a year (INE 2003), and according to our calculations below, the annual cost of traffic delays is $580 per capita. Moreover, pressure on pollution and congestion will continue because the population of the metropolitan area is projected to increase from 19 million today to 26 million by 2020 (Molina and Molina 2002).

Since 1990, several policies have been introduced with the aim of partly alleviating Mexico City's air quality and congestion problems (see, e.g., Sánchez 2000). Many environmental measures are targeted at the transportation sector, which according to O'Ryan and Larraguibel (2000) accounts for around 40 percent of particulate formation and 75 percent of nitrous oxide emissions (a precursor for ozone), the two most serious pollutants from a local public health perspective. These measures include mandates for three-way catalytic converters, progressively more stringent emissions standards for new cars, periodic emissions inspections for in-use vehicles, and the phaseout of leaded gasoline.[1] Policies to alleviate congestion include the Today Don't Drive program, which bans most drivers from using their vehicles one weekday per week (Davis 2007). In addition, mass transit has been upgraded, with a rapid bus system on the main north-south arterial route and high-speed suburban rail links, among other improvements.

Those policies have met with mixed success. Although the trend of rising air pollution during the 1980s and 1990s has been reversed, particulate matter and ozone levels remain well above Mexican air quality standards, in part because growing demand for energy counteracts

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* Corresponding author. Resources for the Future, 1616 P Street NW, Washington DC, 20036. Phone (202) 328-5151; email parry@rff.org; web www.rff.org/parry.cfm. Timilsina is at the World Bank. Parry is grateful to the World Bank for financial support. Ken Small provided very valuable comments on an earlier draft. We also thank Hari Dulal for valuable research assistance.

[1] For discussion and analysis of other pollution initiatives, see INE (2003), Molina and Molina (2002), and West et al. (2003).

reductions in energy intensity (Molina and Molina 2002, Ch. 2; Bell et al. 2006; Davis 2007). And people can evade the no-drive day program by using second vehicles (Eskeland 1992).;

An alternative (and in some respects complementary) strategy for mitigating pollution, congestion, and traffic accidents—one that has not yet been tried in Mexico City—is reforming the system of transportation prices. One option would be to raise the (state-controlled) price of gasoline, which fuels privately operated microbuses as well as passenger cars. Another option is to introduce some form of tolling by the mile for passenger cars, comparable perhaps to the tolls recently introduced in London and Stockholm (ideally, tolls would vary by time of day, but for reasons discussed below, this is beyond our scope). Whether microbuses should be taxed or subsidized on a per mile basis is not immediately clear; although they deter private use of automobiles, they themselves contribute to congestion and pollution. A further possibility is to adjust fares charged to users of the public bus and subway system.

Previous literature offers little in the way of a conceptual and empirical framework for assessing the benefits and costs of these pricing options for Mexico City, understanding which pricing reforms yield the biggest welfare gains, or gauging to what extent transportation prices should be reformed. Such a framework would provide useful guidance for local policymakers alongside other criteria (e.g., distributional impacts, political feasibility, ease of monitoring and enforcement of policy reforms) that are beyond our scope.

Some studies have examined the health impacts of pollution in Mexico City (e.g., Bell et al. 2006; Borja-Aburto et al. 1997; O'Neill et al. 2004; Molina and Molina 2002) but do not examine optimal pricing of multiple travel modes and fuel in the presence of multiple externalities. In the transportation literature, some road network simulation models have been developed and used to quantify the optimal set of prices to deal with pollution and congestion externalities. For the most part, these have been applied to U.S. or European cities (e.g., de Borger and Proost 2001; Safirova et al. 2008). They have not been calibrated and empirically applied specifically to Mexico City or to broadly comparable Latin American cities, at least not in a way that fully accounts for multiple externalities, substitution among travel modes, and fuel price-induced changes in vehicle fuel economy. Moreover, although containing less detail than a sophisticated computational road network model, a conceptual analytical framework could provide explicit formulas for optimal policies and welfare gains from policy reform. This helps clarify why some factors or parameters are important in policy evaluation while others are not; it also makes transparent the implications of different assumptions where parameters are uncertain.

The aim of this paper is to develop such an analytical framework for roughly gauging the appropriate direction and extent of pricing reforms for passenger travel and fuel use in Mexico City. Our theoretical framework shares certain features of some previous analytical models used for optimally pricing gasoline and transit travel in the United States and Europe (Parry and Small 2005, 2008). But to evaluate appropriate policy reforms for Mexico City, we still need to develop a model that captures the special characteristics of its transportation system, such as the widespread use of microbuses, and to compile and estimate the region-specific parameters to feed into the model. Our aim is to provide simple and intuitive formulas for optimal policies and welfare effects that are readily implemented in a spreadsheet, easily updated in the light of future evidence on parameters, and readily applied to similar urban centers in Latin America.

In principle, our analysis suggests that dramatically higher gasoline taxes could be justified on efficiency grounds than the current excise tax of 17 cents per gallon (which itself has recently been scaled back with the runup in world oil prices). Our benchmark estimate of the (second-best) optimal fuel tax is $2.72 (or 29.6 pesos) per gallon (results are somewhat sensitive to alternative parameter values). However, as we discuss later, this policy might be widely evaded if fuel prices in Mexico City rise substantially above those in neighboring regions, a factor that is excluded from our model. Moreover, a far more moderate fuel tax increase of $1 per gallon still achieves substantial welfare gains—about 60 percent of those from the optimal fuel tax increase of $2.57 per gallon.

Although higher fuel taxes help internalize pollution and accident externalities, the largest source of efficiency gain comes from the reduction in automobile congestion. But a more efficient way to reduce congestion would be to impose per mile tolls on automobiles. If this policy were implemented instead of a fuel tax increase, our analysis suggests that the optimal toll on auto mileage (averaged across all driving in the metropolitan area) is 20.3 cents per vehicle mile; this converts, at current fuel economy, to $3.50 per gallon of gasoline used by autos. Again, however, a large portion of the welfare gains under the optimum policy could be generated by a far more modest policy change. For example, we estimate that the welfare gains from a toll of just 6.0 cents per mile are still half of those from the much higher (optimized) toll.

For microbuses, we put the optimized toll per vehicle mile at 34.6 cents in our benchmark calculations. Although the imposition of this toll causes some increase in auto travel, overall road congestion falls. Nonetheless, welfare gains from this policy are more modest than those from gasoline taxes or auto tolls.

Roughly speaking, existing fare subsidies for public bus and rail (which amount to about 50 percent of average operating costs from the transit companies) are not dramatically different from optimal fares in our analysis. Furthermore, the modal shares for mass transit are modest compared with those for autos and microbus. Thus, welfare gains from reforming transit prices are smaller than those from other pricing reforms. In short, the most desirable policy reform from an efficiency and practical perspective appears to be the introduction of per mile tolls on automobiles.

The rest of the paper is organized as follows. The next section lays out our analytical model and derives our optimal pricing and welfare formulas. Section 3 discusses our parameter assumptions. Section 4 presents the main quantitative results and sensitivity analysis. The final section discusses possible ways to help overcome practical and political obstacles to implementing economically efficient policy reforms.

2. Analytical Model

We adopt a model of urban passenger travel by private auto, private microbus, public bus, and public rail (i.e., subway). To varying degrees, transportation vehicles and their fuels contribute to externalities from local and global pollution, accidents, and road congestion. The government sets fuel prices, public transit fares, and mileage tolls for private buses and autos subject to a budget constraint. Although, for tractability, the model is static, it implicitly encompasses long-run, policy-induced changes in vehicle fuel economy and vehicle fleet composition.

A. Justification for Omitted Factors from the Analysis

We do not consider policies that vary either by region within Mexico City or by peak versus off-peak travel. Partly, this is because the data to do this disaggregation (e.g., subregion or time-of-day specific external costs, and the degree of traveler substitution between subregions and time of day) are not available. Nevertheless, it is still logical to begin with a simple and transparent analysis to fully understand the aggregate impacts of major pricing reform options before studying more refined policies that vary by space and time of day and may require a more detailed (and less transparent) transport network model. Given that our focus is on overall efficiency rather than distributional effects (see Section 5), we employ a representative (rather than heterogeneous) agent framework (see Parry and Small 2008 for a defense of this assumption in the study of urban transportation pricing policies).

Our model also omits certain scale economies from expanding transit provision, which may justify fare subsidies (Mohring 1972), though we do include fixed costs for subways. Other scale economies include reduced passenger wait times at transit stops as service frequency increases with a larger transit system, reduced costs of accessing the transit system with expansion of the route network, and the opportunity for transit operators to save on vehicle operating costs by increasing the occupancy of transit vehicles (instead of supplying more vehicle miles). On the other hand, scale economies are counteracted by a diseconomy to the extent that higher transit vehicle occupancy imposes crowding costs on passengers though longer delays while people board and alight, greater likelihood of standing, discomfort, etc. (Kraus 1991). However, we do not have the data to credibly estimate the net impact, let alone the magnitude, of these scale economies and diseconomies, and therefore they are excluded from our analysis.

Prior literature on environmental and transportation taxes emphasizes the potential importance of considering how these policies interact with factor market distortions created by the broader tax system, particularly tax distortions in the labor market. Specifically, the optimal (revenue-neutral) tax on a fuel or travel mode will exceed any level warranted on externality grounds if the fuel or travel mode is a relatively weak substitute for nonwork time (e.g., Bovenberg and Goulder 2002). For the United States, Parry and Small (2005) and West and Williams (2007) estimate the upward adjustment in the optimal gasoline tax to account for broader fiscal interactions. Again, however, the needed empirical evidence to assess this adjustment for Mexico City—particularly the substitution between (taxed) formal work effort and (untaxed) informal work in response to changing transportation prices and income taxes—is not available. Therefore, broader fiscal interactions are also excluded from our analysis.

B. Model Assumptions

(i) Household utility. An agent, representing an aggregation over all individuals in the Mexico City metropolitan area, has utility function $U(.)$ defined by

(1a) $U = u(X, M, T, \overline{E})$

(1b) $M = M(M^A, M^{MB}, M^B, M^R)$

(1c) $T = \sum_i \bar{t}^i M^i$, $\quad i = A, MB, B, R$

All variables are expressed in per capita terms, and a bar indicates a variable at the city level, perceived as exogenous by the individual traveler.

In (1a), function $u(.)$ is quasi-concave and increasing in its first two arguments and declining in the other two arguments. X is consumption of a general good, produced and sold in the formal sector. $M(.)$ is subutility from passenger miles of travel. In (1b), this is increasing in M^A, passenger miles traveled by automobile (including taxi); M^{MB}, passenger miles traveled by private microbus (minibuses and VW buses); M^B, passenger miles traveled by larger, government-provided buses; and M^R, passenger miles traveled by government-provided rail.[2] $M(.)$ is quasi-concave, so alternative travel modes are imperfect substitutes at the aggregate level.

T is in-vehicle travel time spent in trains, buses, and cars, which implicitly lowers utility by reducing time available for leisure and activities in the informal sector. In (1c), total in-vehicle travel time is the average time per mile for mode i (the inverse of vehicle speed), t^i, times total passenger miles traveled by that mode, and aggregated across all four travel modes.

Finally, E is an index of noncongestion externalities. These encompass local pollution, which harms human health, reduces visibility, corrodes buildings, etc., and greenhouse gases, which reduce (future) utility through global warming and associated climate change.[3] E also includes external costs of traffic accidents, such as injury risks to pedestrians and possibly to victims in multivehicle collisions, property damages borne by third parties, etc. (some accident costs are internal, such as own-injury risks in single-vehicle crashes, and these are implicitly incorporated in $u(.)$).

[2] We ignore light rail travel because it accounts for only 0.03 percent of passenger miles in Mexico City (IAPT 2007).

[3] As usual, we view climate change externalities from a world (rather than local) perspective.

(ii) Transportation inputs. We assume that vehicle miles change in proportion to passenger miles for all modes—that is, vehicle occupancy is fixed.[4] Therefore, for analytical purposes, we do not need to distinguish between passenger miles and vehicle miles (implicitly, vehicle miles equals passenger miles divided by a parameter representing vehicle occupancy).

For convenience, we specify the supply-side of the transport system on an aggregate basis. The "production functions" for aggregate miles traveled by each mode are

(2a) $M^i = M^i(K^i, F^i), \quad i = A, MB, B$

(2b) $M^R = M^R(K^R_{FC}, K^R)$

In (2a), K^i represents an aggregate of nonfuel inputs needed to run vehicles of type i. For buses, these include the number of vehicles in the fleet (expressed on a capacity-equivalent basis), which can be varied fairly easily in the medium term, as well as the manpower required to drive vehicles. For private autos, K^A reflects only vehicle capital costs, since the value of motorists' own time is incorporated via T in the utility function. For subways in (2b), we distinguish fixed factors associated with labor required to operate stations, K^R_{FC}, from the variable inputs required for vehicle operation, K^R. Capital infrastructure for subways, namely tracks and stations, is excluded from K^i. Thus, we follow the usual practice of studying how best to price rail systems given existing infrastructure, without worrying about recovering previously sunk capital investments in current fares.

In (2a), F^A and F^{MB} denote aggregate gasoline used by autos and microbuses, respectively, and F^B denotes aggregate diesel fuel used by public buses. In (2b), we exclude fuels (associated with the electricity consumption of trains) because environmental costs from fuel use, when expressed on a per passenger mile basis, are very small, given the very high occupancy of trains with several cars (Parry and Small 2008).

We assume the production functions in (2a) are increasing, quasi-concave, and homogeneous of degree one. Thus, there are constant returns to scale in the supply of auto and bus vehicle miles, which seems a reasonable approximation (Small and Verhoef 2007, 65). For a given amount of auto or bus mileage, a reduction in the amount of fuel and an increase in other inputs represent a long-run shift in the fleet toward more fuel-efficient but more capital-intensive

[4] This is reasonable for transit, given that we do not model scale economies and diseconomies from changes in vehicle occupancy. And although car pooling may increase with higher auto taxes, we believe this would have little effect on our policy simulations.

vehicles (e.g., because of the advanced fuel-saving technologies incorporated into newer vehicles). For (2b), we assume the supply of rail passenger miles is proportional to variable inputs (i.e., $dM^R / dK^R > 0$ is constant), which seems reasonable.

(iii) Transportation prices. The government imposes cordon tolls or congestion fees on private autos and microbuses, which we represent by a per mile tax of $\delta^i \geq 0$ ($i = A$, MB) when averaged over all mileage in the metropolitan area. The price of gasoline and diesel are given by p^G and p^D, respectively; these prices are set by the government via state ownership of fuel production.[5] For all vehicles, we normalize the price of other market inputs, K^i, to unity. And for transit vehicles, we denote the fare charged per passenger mile by p^i ($i \neq A$).

Microbus service is provided by a large number of competitive enterprises. In the zero-profit equilibrium, passenger fares equal (constant) variable operating costs per mile, which include fuel costs, labor costs, capital costs, and taxes. Thus,

$$(3) \qquad p^{MB} = \left(p^G F^{MB} + K^{MB}\right) / M^{MB} + \delta^{MB}, \qquad j = D, C$$

(iv) Other production. All goods, fuels, and vehicles are produced under constant returns to scale with labor as the only primary input (implicitly, vehicle capital is an intermediate input produced with labor).

(v) Household constraints and optimization. Agents are subject to the following budget constraint, which equates income with spending on auto fuel, auto capital, auto taxes, transit fares, and the general market good (whose price is normalized to unity):

$$(4) \qquad I + \overline{GOV} = p^G F^A + K^A + \delta^A M^A + \sum_{i \neq A} p^i M^i + X$$

Here I is exogenous income (implicitly from a fixed amount of work effort). $\overline{GOV}$ is per capita government spending on a transfer payment to households. This closes the model by requiring

[5] The government is assumed to supply whatever fuel is demanded at these prices so that there is no rationing of fuel.

that any increase or decrease in government revenue from changing transportation prices be received (or paid for) by households.[6]

Agents choose the general good, auto inputs, and transit travel (and thereby travel times) to maximize utility (1) subject to the budget constraint (4) and the auto production function in (2a), taking unit travel times and external costs as given. This yields

$$\text{(5a)} \qquad \frac{u_{M^A} + u_T t^A}{u_X} = p^G \frac{F^A}{M^A} + \delta^A, \qquad \frac{u_{M^i} + u_T t^i}{u_X} = p^i, \qquad i \neq A$$

$$\text{(5b)} \qquad \left(\frac{u_{M^A} + u_T t^A}{u_X} - \delta^A \right) M^A_{F^A} = p^G, \qquad \left(\frac{u_{M^A} + u_T t^A}{u_X} - \delta^A \right) M^A_{K^A} = 1$$

where the denominator u_X converts utils into consumption or monetary units. In (5a), the marginal private benefit from auto passenger mileage, net of the cost of travel time (i.e., the marginal value of time $-u_T / u_X$ multiplied by time per mile t^A), is equated with per mile fuel costs and any auto toll. In addition, the marginal private benefit from mass transit travel, less time costs, is equated with the per mile fare. In (5b), the extra mileage (or "marginal product") from auto fuels and auto vehicle capital ($M^A_{F^A}$ and $M^A_{K^A}$), times the marginal private benefit from auto travel, net of travel time costs and the mileage tax, are equated with the fuel price and the price of vehicle capital, respectively.

(vi) Per unit travel times and external costs. We define the following:

$$\text{(6a)} \qquad t^i = t^i(\tilde{M}), \qquad \tilde{M} = \overline{M}^A + \beta^{MB} \overline{M}^{MB} + \beta^B \overline{M}^B, \qquad i \neq R, \qquad t^R = \bar{t}^R$$

$$\text{(6b)} \qquad \beta^{MB} = \frac{\sum_{i \neq R} t^i_{MB} M^i}{\sum_{i \neq R} t^i_A M^i}, \qquad \beta^B = \frac{\sum_{i \neq R} t^i_B M^i}{\sum_{i \neq R} t^i_A M^i},$$

where $t^i_{MB} = dt^i / dM^{MB}$, etc.

Beginning with (6b), β^{MB} and β^B denote "passenger car equivalents" for microbus and bus. These reflect the addition to congestion (i.e., the increase in travel time for all passengers of

[6] Any income effects on passenger travel from changes in the transfer payment are implicitly included in the calibration of travel demand responses below. These income effects are relatively minor, given that spending on auto or transit travel represents a relatively minor fraction of the household budget constraint (Willig 1976).

road vehicles) from one extra *passenger* mile by a microbus or bus ($\sum_{i \neq R} t^i_{MB} M^i$ or $\sum_{i \neq R} t^i_B M^i$), expressed relative to the additional congestion from one extra passenger mile by car ($\sum_{i \neq R} t^i_A M^i$). An extra *vehicle* mile by a bus adds more to congestion than an extra *vehicle* mile by a car because buses take up more road space and stop frequently. However, because of buses' much larger passenger occupancy, an additional *passenger* mile by bus may add less to congestion than an extra passenger mile by auto (in which case β^{MB} and β^B are less than one).

In (6a), average travel time per mile for a road vehicle is an increasing function of passenger car equivalent mileage $\tilde{M}$. The latter is simply the sum of passenger miles across cars, microbuses, and public buses, where each are weighted by their passenger car equivalents. Train time per mile is taken to be constant—that is, running an additional train does not slow down other trains in the system.

Noncongestion external costs are given by

(7) $$E = E(F^G, M^A, M^{MB}, M^B)$$

where E is weakly increasing in all its arguments and $F^G = F^A + F^{MB}$ is combined gasoline consumption from cars and microbuses. The partial derivatives of this function denote various marginal external damages (in utils). For example, $\partial E / \partial F^G$ is the marginal externality from gasoline use, reflecting CO_2 and local emissions, and $\partial E / \partial M^A$ is the marginal external cost of traffic accidents from automobile mileage. Following an increase in the gasoline tax, the proportionate reduction in gasoline-related externalities exceeds the proportionate reduction in auto and microbus mileage-related externalities. This is because the former reflects both long-run changes in average vehicle fuel economy and reductions in vehicle mileage, whereas the latter reflects only changes in mileage (see Parry and Small 2005 for further discussion). In contrast, diesel fuel and public bus mileage always change in the same proportion in our analysis, since diesel prices are fixed. Thus, there is no need to decompose diesel fuel externalities from public bus mileage externalities; implicitly, they are both incorporated in $\partial E / \partial M^B$.[7]

[7] If new vehicles are subject to binding emissions per mile standards, then emissions of new vehicles are independent of fuel economy because all vehicles meet the same standard regardless of their fuel economy. In practice, the decoupling of emissions from fuel economy is undermined to the extent that emissions control equipment deteriorates over the vehicle life, older vehicles (not initially subject to standards) are still in use, people can evade emissions inspections for in-use vehicles, and fugitive emissions come from petroleum refining

(vii) Government. The government is subject to the budget constraint

(8a) $$GOV = \sum_i \delta^i M^i + \delta^G F^G - K^R_{FC}$$

(8b) $$\delta^G = p^G - \theta^{FG}, \qquad \delta^B = p^B - \theta^B, \qquad \delta^R = p^R - \theta^R$$

(8d) $$\theta^B = \left(\theta^{FB} F^D + K^B\right) / M^B, \qquad \theta^R = K^R / M^R$$

In these equations, θ^{FG} and θ^{FB} denote a constant per unit cost incurred by a state-owned enterprise for producing gasoline and diesel fuel, respectively (resource inputs, refinery and distribution costs, etc.). θ^B and θ^R are the (constant) marginal costs to the government of supplying a passenger mile for public bus and rail. They include (variable) capital and labor costs and, in the case of bus, fuel costs.

δ^G is the (effective) gasoline excise tax charged to private vehicle operators. It equals the difference between the government-determined fuel price, and the unit production cost of the fuel. δ^B and δ^R reflect the difference between the fare for public bus and rail charged to passengers and the marginal cost to the government agency of supplying passenger miles; these price wedges can be negative if transit fares are subsidized.

The budget constraint in (8a) equates the government transfer payment with revenues from policy variables, namely auto and microbus mileage tolls, profits to state-owned fuel producers, and passenger fares, less the variable and fixed costs of transit provision.

C. Formulas for Optimal Policies and Welfare Effects

We now discuss formulas for the optimal pricing of fuels and passenger travel by mode and for the welfare gains from policy reforms, for a given set of prices for other fuels and modes. We take policies one at a time (implicitly viewing them as alternatives), though our formulas clarify how the optimal level of one policy varies with the level of other policies. Here we go straight to the key equations; the analytical derivations are provided in Appendix A.

(Harrington 1997). We believe these factors are significant for Mexico City, and therefore assuming proportionality between local emissions and gasoline use is a reasonable approximation.

(i) Optimal gasoline tax. To start, we discuss a formula for the marginal welfare effect from raising the gasoline tax. This formula is derived by totally differentiating the household's indirect utility function with respect to δ^G, accounting for changes in external costs, per unit travel times, and *GOV* to maintain government budget balance. The formula is as follows (Appendix A):

(9a) $$(E^G - \delta^G)\left(-\frac{dF^G}{d\delta^G}\right) + (E^A - \delta^A)\left(-\frac{dM^A}{d\delta^G}\right) + (E^{MB} - \delta^{MB})\left(-\frac{dM^{MB}}{d\delta^G}\right) + \Gamma_G$$

(9b) $$\Gamma_G = (\delta^B - E^B)\frac{dM^B}{d\delta^G} + \delta^R \frac{dM^R}{d\delta^G}$$

(9c) $$E^G = -u_{\bar{E}} E_{F^G} / u_X$$

(9d) $$E^k = -u_{\bar{E}} E_{M^k} / u_X + E^{CONGk}, \;\; E^{CONGk} = -\beta^k \frac{u_T}{u_X} \sum_{i \neq R} t^i_{\tilde{M}} M^i, \; k = A, MB, B, \;\; \beta^A = 1$$

We first define the new notation before interpreting the main equation in (9a). In (9c), E^G is the marginal external cost of gasoline, expressed in dollars. In (9d), E^k is the marginal external cost of passenger miles by auto, microbus, or public bus. These include marginal accident costs, marginal congestion costs E^{CONGk}, and (for public bus) pollution costs from diesel fuel use. E^{CONGk} is the increase in per passenger mile travel time for a road vehicle due to congestion caused by an passenger mile by auto, microbus, or public bus ($t^i_{\tilde{M}}$, $\beta^{MB} t^i_{\tilde{M}}$, and $\beta^B t^i_{\tilde{M}}$, respectively) multiplied by the corresponding passenger mileage for those modes, aggregated over modes, and multiplied by the marginal value of travel time.

Equation (9a) decomposes the welfare effect of an incremental increase in the gasoline tax into four components. First is the welfare change in the gasoline market, equal to the reduction in gasoline use, times the marginal external cost of gasoline net of the prevailing gasoline tax. The second and third terms in (9a) are the reduction in microbus and bus passenger miles (induced by higher gasoline taxes) multiplied by the marginal external cost of passenger travel for those modes, less any prevailing per mile tolls on those modes. Finally, Γ_G in (9a) captures secondary welfare effects due to substitution out of auto and microbus into public bus and rail, though these effects are of minor importance in our simulations (given the small modal shares for public transport).

Equating (9a) to zero, we obtain the optimal (second-best) gasoline tax δ^{G*} in cents per gallon:

(10a) $\delta^{G*} = E^G + (E^A - \delta^A)\rho_{AG} + (E^{MB} - \delta^{MB})\rho_{MBG} + \gamma_G$

(10b) $\gamma_G = (E^B - \delta^B)\rho_{BG} - \delta^R \rho_{RG}$

(10c) $\rho_{jG} = \dfrac{dM^j / d\delta^G}{dF^G / d\delta^G}, \quad j = A, MB, B, R$

In (10c), the relative price coefficient ρ_{jG} denotes the change in passenger mileage on mode *j* per unit change in gasoline use, following an increase in the gasoline tax.

In (10a), the optimum gasoline tax equals the pollution cost per gallon of gasoline plus the external cost per passenger mile for auto and microbus (net of any per mile tax) where each is multiplied by the (reduction) in passenger miles for that mode relative to the (reduction) in gasoline use. The γ_G term captures the (empirically small) influence of transit cross-price effects on the optimal gasoline tax.

(ii) Optimal mileage toll for autos. Following a similar procedure to that above, the optimal tax per passenger mile on automobiles in cents per mile (for given prices of other modes and fuels), δ^{A*}, is as follows (Appendix A):

(11a) $\delta^{A*} = E^A + (E^G - \delta^G)\rho_{GA} + (E^{MB} - \delta^{MB})\rho_{MBA} + \gamma_A$

(11b) $\gamma_A = (E^B - \delta^B)\rho_{BA} - \delta^R \rho_{RA}$

(11c) $\rho_{jA} = \dfrac{dM^j / d\delta^A}{dM^A / d\delta^A}, \quad j = MB, B, R; \quad \rho_{GA} = \dfrac{dF^G / d\delta^A}{dM^A / d\delta^A}$

(The optimal auto toll can alternatively be expressed per *vehicle* by multiplying δ^{A*} by auto occupancy, and similarly for the microbus toll discussed below).

In (11c), the relative price coefficients are now defined for an increase in the auto mileage toll (rather than the gasoline tax), and the denominator in these expressions is the own-price effect on auto mileage. In (11a), the optimal toll equals the marginal congestion and accident externality per auto passenger mile plus the product of the marginal reduction in gasoline use and the marginal external cost of gasoline, net of the prevailing gasoline tax. The optimal auto toll is lower to the extent it encourages the diversion of travel onto microbus and there are positive external costs to microbus travel (net of any microbus tolls). Finally, γ_A

captures cross-price effects with public bus and rail, which again play only a minor role in the simulations.

The main difference between the auto mileage toll and the gasoline tax is that the mileage toll targets the congestion and accident externalities more directly because all the behavioral response to the tax comes from reduced mileage (rather than part of it coming from improved fuel economy). In addition, microbus mileage may increase in response to the auto toll (given that microbuses are not tolled), but it declines in response to higher gasoline prices (which are passed forward into passenger fares).

(iii) Optimal toll for microbus. The optimal toll per passenger mile by microbus, δ^{MB*}, is as follows (Appendix A):

(12a) $\delta^{MB*} = E^{MB} + (E^G - \delta^G)\rho_{GMB} + (E^A - \delta^A)\rho_{AMB} + \gamma_{MB}$

(12b) $\gamma_{MB} = (E^B - \delta^B)\rho_{BMB} - \delta^R \rho_{RMB}$

(12c) $\rho_{jMB} = \dfrac{dM^j / d\delta^{MB}}{dM^{MB} / d\delta^{MB}}, \quad j = AB, B, R; \quad \rho_{GMB} = \dfrac{dF^G / d\delta^{MB}}{dM^{MB} / d\delta^{MB}}$

These equations are analogous to those for the optimal auto mileage toll, with the relative price coefficients now defined with respect to an increase in the microbus toll. As discussed below, increased auto travel in response to higher microbus tolls (and therefore fares) can significantly affect the optimal microbus toll, given that auto absorbs a significant portion of diverted microbus passengers and the significant external costs per auto passenger mile.

(iv) Optimum fare for public bus and rail. The optimal fare per mile for public bus is as follows (Appendix A):

(13a) $p^{B*} = \theta^B + E^B + (E^A - \delta^A)\rho_{AB} + \gamma_B$

(13b) $\gamma_B = (E^G - \delta^G)\rho_{GB} + (E^{MB} - \delta^{MB})\rho_{MBB} - \delta^R \rho_{RB}$

(13c) $\rho_{jB} = \dfrac{dM^j / d\delta^B}{dM^B / d\delta^B}, \quad j = A, MB, R; \quad \rho_{GB} = \dfrac{dF^G / d\delta^B}{dM^B / d\delta^B}$

The optimal fare consists of the marginal cost of supplying passenger miles, plus any external cost per passenger mile for bus travel. In addition, the fare is lower to the extent that reducing it would divert people from autos onto public bus (and external costs from auto mileage exceed any auto mileage toll). The fare also depends on (empirically minor) cross-price effects on fuels and other transit modes, as captured in the γ_B term.

The optimal fare for rail is essentially analogous to that for public bus. However, unlike in (13a), there are no external costs for rail, while in the analogous expression to (13b) the cross-price effect on public bus, $(E^B - \delta^B)\rho_{BR}$, now includes external costs.[8]

(v) Functional forms. We take accident costs per mile and pollution costs per unit of fuel as given. However, we allow marginal congestion costs to fall as policies discourage road traffic. For the time to travel a passenger mile by auto, we adopt the following formulation:

$$(15) \qquad t^A = \alpha\left\{1 + \gamma\left(\frac{\tilde{M}}{\tilde{M}^0}\right)^4\right\}$$

where α is the time per mile by auto at free-flowing traffic speeds and γ is a parameter. Under this formulation, average delay per mile due to congestion over free-flowing speeds is $\alpha\gamma(\tilde{M}/M^0)^3$, and marginal delay is $4\alpha\gamma(\tilde{M}/M^0)^3$, so marginal delay is four times average delay.[9] This formula is used to compute the (endogenous) marginal congestion costs for auto. Marginal congestion costs for microbus and public bus are also obtained from this formula, using their passenger car equivalents.

The own-price effects on fuel use and travel demand are determined by the constant elasticity specifications:

$$(16a) \quad F^G = F^{G0}\left(\frac{p_G}{p_G^0}\right)^{\eta_{GG}}$$

$$(16b) \quad M^A = M^{A0}\left(\frac{p_G F^A / M^A + \delta^A}{p_G^0 F^{A0} / M^{A0}}\right)^{\eta_{AA}}, \quad M^{MB} = M^{MB0}\left(\frac{p_G F^{MB} / M^{MB} + \delta^{MB}}{p_G^0 F^{MB0} / M^{MB0}}\right)^{\eta_{MBMB}}$$

[8] Note that relative price coefficients defined with respect to the price of public bus and rail implicitly account for feedback effects of road congestion. For example, raising the rail fare will divert people onto road, thereby exacerbating road congestion, which in turn partly offsets the added attractiveness of road travel when rail fares go up. These feedback effects are implicit in the choice of values for the ρs below.

[9] This seems a reasonable assumption, based on empirical relationships for Toronto and Boston, discussed in Small (1992, 70–71).

(16c) $M^{B} = M^{B0}\left(\frac{p_B}{p_B^0}\right)^{\eta_{BB}}$, $M^{R} = M^{R0}\left(\frac{p_R}{p_R^0}\right)^{\eta_{RR}}$

where superscript 0 denotes an initial value.

In these equations, η_{GG} denotes the own-price elasticity of gasoline demand, and η_{AA}, η_{MBMB}, η_{BB}, and η_{RR} denote own-price elasticities for auto mileage, microbus mileage, public bus mileage, and rail mileage, respectively. In (16a), fuel demand is a simple function of fuel price relative to its initial level. In (16b), auto travel is a simple function of fuel costs and possible congestion tolls, all expressed on a per mile basis and relative to the initial price. The same applies for microbus mileage, given that fuel costs and tolls are passed forward into passenger fares.[10] And in (16c), passenger miles by public bus and rail are a simple function of own transit fares.

As for cross-price effects, the effect on another mode *k* following an increase in the price of mode *i* is simply given by

(17) $M^{k} = M^{k0} - \int_{p^{i0}}^{p^{i}} \rho^{ji} \frac{dM^{i}}{dp^{i}} dp^{i}$

where the absolute price coefficient $dM^{i} / dp^{i} = \eta^{ii} M^{i} / p^{i}$ is calculated using (16) and assumed values for elasticities.

(vi) Welfare effects. The per capita welfare effect from a marginal increase in the gasoline tax and a marginal increase in the auto toll, respectively, are as follows (Appendix A):

(18a) $\frac{1}{u_X}\frac{du}{d\delta^G} = -\left(\delta^{G*} - \delta^{G}\right)\frac{dF^{G}}{dp^{G}} = -(\delta^{G*} - \delta^{G})\frac{\eta_{GG}F^{G}}{p^{G}}$

(18b) $\frac{1}{u_X}\frac{du}{d\delta^A} = -\left(\delta^{A*} - \delta^{A}\right)\frac{dM^{A}}{d\delta^{A}} = -\left(\delta^{A*} - \delta^{A}\right)\frac{\eta_{AG}M^{A}}{p^{G}}$

In (18a), starting with the current gasoline tax, we can numerically integrate this expression, using the demand function in (16a), to obtain the welfare gain from any (nonmarginal) increase

[10] Note that the effect of incremental increases in the fuel tax on mileage will decline somewhat as higher prices reduce fuel use per mile, via improved fuel economy. In addition, auto and microbus travel demands are not explicit functions of time costs per mile, which decline (moderately) with less traffic. That is, the feedback effect of less congestion on stimulating latent travel demand is implicitly taken into account in our chosen values for η_{AA} and η_{MBMB}. This is consistent with the way these elasticities are typically estimated in the empirical literature.

in the fuel tax. This welfare gain is illustrated in Figure 1 (for a linear demand curve; demand is slightly convex under our constant elasticity specification). The welfare gain is the shaded trapezoid area between the fuel price evaluated at the optimal gasoline tax ($p^G(t_G^*)$), and the gasoline demand curve, with base equal to the reduction in gasoline.

Similarly, using (18b) and (16b), we can integrate over marginal price effects to calculate the welfare effect from a nonincremental auto toll. Welfare gains from microbus tolls and changes in public bus and rail fares can be obtained in analogous ways.

3. Data

Appendix B provides an extensive discussion of data sources and various estimation procedures for all parameters needed to compute the above formulas. Here we comment on selected baseline data, which are for year 2005 or thereabouts, summarized in Table 2. We express monetary figures in U.S. dollars for year 2005; these values are easily converted to local currency using the (average) 2005 exchange rate of 10.90 Mexican pesos per U.S. dollar.

We caution against taking the baseline parameter assumptions and later simulation results too literally. For one thing, direct estimates of external costs and behavioral responses to transportation policies for the Mexico City region are sparse. Therefore, often we need to extrapolate evidence from other countries (notably the United States). Though providing reasonable first-pass estimates, these measures should be checked against future empirical studies employing data on local factors. Another caveat is that we have less confidence in the marginal welfare effects of price changes at price levels that are very different from those currently prevailing because of uncertainty over functional form relationships. Thus, results from our base case parameter assumptions are meant to provide only a ballpark sense of optimal policies and the appropriate direction of policy reform. The implications of alternative parameter values are illustrated in a later sensitivity analysis.

A. Basic Data for the Transport Network

Most of our data come from the Millennium Cities Database for Sustainable Transport (IAPT 2007). In 2005, per capita passenger mileage aggregated across all modes was 5,588 miles; 67 percent of this mileage was by private auto (and taxi), 19 percent by microbus, 7 percent by larger public buses, and 8 percent by subway. Vehicle occupancies are 1.6 people for autos, 8 for microbuses, 31 for public buses, and 174 for trains (which pull several cars). All these figures are for the entire metropolitan area of Mexico City, including the suburbs. (For the downtown core alone, the share of mileage by the three mass transit modes, as well as vehicle occupancies, would be larger.)

Average vehicle fuel economy for autos is 17.4 miles per gallon. The baseline fuel economy for microbuses and public buses is approximately one-half and one-quarter that for autos. However, when expressed in terms of passenger miles rather than vehicle miles, fuel economy is far greater for buses than for autos because of their much larger passenger occupancies. Overall gasoline consumption per capita is 149 gallons, with 88 percent of this used by autos and 12 percent by microbus.

The excise tax on gasoline was 17 cents per gallon in 2005. This tax rate is much lower than the rates typically levied in European countries (Parry et al. 2007, Figure 2) and even the United Sates, where the federal and state taxes combined are currently 40 cents per gallon. In fact, the tax in Mexico was progressively reduced to dampen the impact of higher world oil prices on the retail fuel price; only three years earlier the tax had been 87 cents per gallon. Retail fuel prices for 2005 were \$2.21 per gallon (implying a production cost per gallon of \$2.21 − 0.17 = \$2.04).

B. External Costs

The Mexico City basin is especially susceptible to air quality problems because its high altitude and surrounding mountains which limit pollution dispersion. We assume that local pollution damages per gallon of gasoline amount to 90 cents per gallon, where the huge bulk of the damage reflects mortality risk. This figure is based on a compromise between two sources. First is an extrapolation from a study for Los Angeles (another region with topography and climate especially favorable to pollution formation) by Small and Kazimi (1995), adjusted for differences in population exposure, the value of health risks, and vehicle emission rates between the two regions. Second is a study of the health benefits from reducing future pollution concentrations in Mexico City (and two other cities) by Bell et al. (2006), based on pooling epidemiological evidence and the valuation of health risks from various sources (we consider only the mortality effects). As in other studies, we assume that the health and environmental damages per gallon are the same for gasoline and diesel (see Appendix B).

From the mainstream climate damage assessment literature, we assume the damage cost per ton of CO_2 is \$10, which converts to 9 and 11 cents per gallon of gasoline and diesel, respectively (given the carbon content of these fuels). A few studies estimate far larger damages either because they employ much lower discount rates or because they assume a risk of arbitrarily large damages (e.g., through a climate feedback effect causing extreme warming). We therefore consider other values later.

Marginal congestion costs for autos are put at 17 cents per passenger mile. As discussed in Appendix B, this is based on observed travel delays of 0.037 hours per mile (relative to travel times under free-flowing traffic), equation (15), and evidence suggesting the value of travel time is about half the market wage, currently about \$4 per hour. (Using these figures and annual mileage also gives our figure of \$580 in congestion costs per capita, mentioned in the introduction). In addition, parameter γ in equation (15) is taken to be 1.121; this implies, for example, that a 20 percent reduction in road traffic will lower average travel times by 26 percent. For microbus and public bus, we assume passenger car equivalents of 3 and 5, respectively (again, based on U.S. studies). However, given the much higher occupancies of transit vehicles, marginal congestion costs per passenger mile are computed at 11 and 4 cents for microbus and public bus, respectively.

Accident costs are extrapolated from U.S. studies (accounting for differences in accident rates). They are taken to be the same on a per vehicle mile basis for autos, microbuses, and public buses for reasons noted in Appendix B. On a per passenger mile basis, accident costs are small (7 percent) relative to marginal congestion costs, reflecting the severe congestion in Mexico City.

C. Behavioral Responses

A substantial body of empirical work considers the responsiveness of gasoline consumption and auto mileage to fuel prices for the United States and certain other industrialized countries (see, e.g., surveys by Goodwin et al. 2004 and Glaister and Graham 2002). Based on this evidence and making some allowance for the greater responsiveness of auto mileage in Mexico City, given the wide array of alternative mass transit options, we assume a gasoline price elasticity of –0.6 and auto and microbus passenger mileage–fuel price elasticities of –0.3. These assumptions are broadly in line with the one study we aware of that estimates behavioral responses with Mexican data (Eskeland and Feyzioglu 1994). (As already noted and discussed further below, applying economy-wide evidence on fuel price elasticities to fuel tax increases that are specific to Mexico City is problematic because it does not capture incentives for obtaining low-tax fuel from neighboring regions of the country, either legally or illegally.)

Own-fare elasticities for passenger mileage by public bus and rail are taken to be –0.5 and –0.3, again based on a body of empirical literature, largely for the United Sates (see Appendix B). To obtain the relative price coefficients when a toll is imposed on auto travel, we assume that 80 percent of the passenger mileage diverted from auto will go onto other modes (according to their shares in nonauto passenger travel), and 20 percent will reflect reduced overall travel demand.[11] When the price of transit increases, however, many travelers are limited in their ability to substitute into auto, given that only a minority of the population owns automobiles (IAPT 2007). For this case, we assume that 30 percent of diverted travel from the transit mode whose price is increased reflects reduced overall travel demand, and of the remaining 70 percent, half goes to auto and half to other transit modes (again in proportion to their shares in other transit mileage). The same modal diversion ratios apply for fare reductions. Finally, when the price of auto and microbus both increase together following an increase in gasoline taxes, we assume that 40 percent of diverted travel reflects overall travel demand, with the remainder going to public bus and rail in proportion to their modal shares.

4. Results

We take each policy in turn and discuss its optimal level and the welfare gains from policy reform under our baseline parameter assumptions. We then briefly comment on how the main results are affected by alternative parameter assumptions.

A. Optimal Gasoline Tax

Table 3 shows our computation of the (second-best) optimal tax on gasoline. The optimal tax is $2.72 per gallon. Local pollution damages account for 90 cents, or 33 percent, of this optimal

[11] For example, for a reduction of 10.0 auto passenger miles in response to higher auto tolls, 4.5 passenger miles are diverted onto microbus, 1.6 to public bus, and 1.9 to rail, and 2.0 reflect reduced overall travel demand.

tax. Global warming damages, however, account for only 9 cents, or 3 percent. The most important component is reduced congestion externalities due to the effect of higher fuel prices on deterring automobile use, which accounts for 131 cents, or 48 percent, of the optimal tax. Even though only half of the reduction in auto fuel use comes from reduced driving (as opposed to long-run improvements in vehicle fuel economy), the congestion benefits still imply a relatively large efficiency gain, given the large size of the congestion externality. Reduced auto accidents contribute 18 cents to the optimal tax, or 7 percent. Reduced congestion and accidents from lower microbus mileage contribute 25 cents to the optimal tax, or 9 percent, reflecting the modest share of gasoline consumed by microbus (initially 12 percent). Finally, cross-price effects onto public bus and rail have a negligible impact on reducing the optimal tax. This reflects their modest modal shares and modest external costs per passenger mile (relative to externality benefits per passenger miles from autos).

Raising the gasoline tax to its optimal level would increase the retail gasoline price from $2.21 to $4.76 per gallon, or by 215 percent, which would reduce gasoline use by 36.9 percent and generate annual welfare gains of $131.8 per capita (Table 3). However, 63 percent of those welfare gains could be obtained by a more moderate increase in the fuel tax, of $1 per gallon. The reason for this is easily seen from Figure 1. Although the base of the welfare gain trapezoid increases with higher fuel taxes, this is partly offset because its average height is falling, so the welfare gain increases by less in proportion to the tax increase.

B. Optimal Auto Toll per Vehicle Mile

Under the benchmark parameter assumptions, and with other taxes fixed at their current levels, the optimal auto mileage toll is 20.3 cents per vehicle mile (see Table 4). This is equivalent to 12.7 cents per passenger mile, or a fuel tax increase (for autos only) of $3.50 per gallon at current auto fuel economy. Local and global pollution justify a mileage toll equivalent to 71 and 7 cents per gallon, respectively; these are somewhat lower than marginal pollution damages per gallon because of partially offsetting pollution as microbus expands to accommodate some diverted auto passengers. In addition, the currently prevailing fuel tax (less extra fuel tax payments from microbuses) is netted out of the optimal auto toll; this lowers the optimal toll by 0.8 cents per vehicle mile. Congestion is easily the largest component of the optimal toll, accounting for 16.9 cents per mile, or $2.95 in equivalent fuel taxation. The congestion component is more than twice as large in the optimal mileage toll as in the optimal gasoline tax. This is because all, rather than 50 percent, of the behavioral response to the mileage toll comes from reduced driving and lower congestion. For the same reason, the accident component is also larger, 1.9 cents per mile, though it is easily dominated by the congestion component. On the other hand, substitution into microbus offsets some of the congestion benefits and lowers the optimal toll by 2.3 cents per mile. Substitution effects into public bus and rail are again too small to matter.

Implementing the optimal toll would reduce auto mileage by an estimated 24.8 percent and generate per capita welfare gains of $109. But again, a large amount of these gains would be captured through a much more modest tax increase. For example, a toll of 6 cents per mile (equivalent to about $1 per gallon on auto fuel) generates welfare gains of $55 per capita.

C. Optimal Microbus Toll per Vehicle Mile

As shown in Table 5, under our benchmark parameters, the optimal toll for microbuses (with all other taxes at their initial levels) is 34.2 cents per vehicle mile. This is equivalent to a tax of $2.67 per gallon of gasoline consumed by microbuses, at current microbus fuel economy. Microbus congestion and accidents alone actually justify a much larger toll, of 79.8 cents per mile, given our assumption that microbuses contribute three times as much to congestion as autos per vehicle mile. However, there is an offsetting reduction of 46.2 cents per mile in the optimal toll as auto mileage expands to accommodate some of the displaced microbus passengers.[12] The contribution of pollution, even local pollution, is relatively small for microbus tolls. In part, this is because 74 percent of the pollution benefits from reduced microbus travel are offset by more pollution from autos.

The optimized microbus toll reduces microbus mileage by 21.2 percent. This generates a welfare gain of $8.60 per capita, or only 6.5 percent of the welfare gains from optimizing the auto toll. Again, a large portion of the welfare gains can be obtained by far more moderate tolls. For example, a toll of 12 cents per microbus mile generates a welfare gain of $5 per capita, or 58 percent of that from the optimized toll.

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[12] For each reduced vehicle mile by microbus, 8 passenger miles are diverted, of which 2.8 go to auto, thereby increasing auto vehicle miles by 1.75. Given that an extra auto mile contributes one-third of the congestion of an extra microbus mile, 58 percent of the reduced congestion from microbus is offset by increased auto travel.

D. Optimum Passenger Fare for Public Bus and Rail

Table 6 shows the optimum fares for public bus and rail. For bus, diverting people off auto onto transit justifies a subsidy of 7.3 cents per passenger mile because of the reduced congestion and other externalities. And diverting passengers off other modes, particularly microbus, justifies a further subsidy of 3.4 cents per passenger mile. Counteracting this, the contribution of public buses themselves to pollution, accidents, and congestion adds 5.3 cents to the optimal fare. Overall, the optimum fare is 5.1 cents per passenger mile, about half the operating cost and very close to the currently prevailing fare.

For rail, diverting passengers away from auto and other modes (especially microbus) justifies a similar subsidy, of 11.4 cents per passenger mile. However, rail has no offsetting increase in externalities from extra travel by this transit mode, implying a wider difference between marginal supply costs per passenger mile and the optimum fare. In fact, the optimum fare is actually negative in these simulations.

We would not put too much emphasis on the precise numbers here, since we used approximations and judgments to set all the parameter values and we ignored broader-scale economies and diseconomies in transit provision. Nonetheless, the results do at least suggest that current fares might be in the right ballpark or perhaps even too high; that is, our analysis suggests there might not be a strong efficiency case for scaling back current fare subsidies (see Parry and Small 2008 regarding other urban centers). Moreover, when combined with the relatively modest modal shares of public bus and rail, the welfare gains from reforming transit prices are smaller than those from raising auto taxes in particular. This is underlined in the last row of Table 6, which shows that lowering current fares by 1 cent per passenger mile produces welfare gains of $0.30 and $2.80 per capita for public bus and rail, respectively, which are small compared with the welfare gains from higher gasoline taxes.

E. Sensitivity Analysis

Table 7 illustrates the sensitivity of optimal gasoline taxes, auto mileage tolls, and microbus tolls to alternative values for selected parameters. We vary the pollution damages per gallon of gasoline, the marginal costs of road congestion, the mileage–fuel price elasticities for auto and microbus, the initial fuel economy for autos and microbuses, and the fraction of reduced demand in response to pricing one mode that comes from reduced overall travel demand (as opposed to substitution into other modes).

The results are sensitive to the parameter perturbations in Table 7 in some cases but not in others. For example, when we double and halve (local and global) pollution damages per gallon of gasoline, the optimal gasoline tax varies between \$2.22 and \$3.71 per gallon, and the optimal auto toll varies between 24.8 and 18.1 cents per vehicle mile. Similarly, doubling and halving marginal congestion costs causes the optimal gasoline tax to vary between \$2.13 and \$3.73 per gallon, the optimal auto toll to vary between 12.4 and 32.6 cents per vehicle mile, and the optimal microbus toll to vary between 17.0 and 67.7 cents per vehicle mile. Varying the mileage–fuel price elasticity affects the optimal gasoline tax because it alters the congestion and accident benefits per gallon of fuel reduction, but it does not affect optimal mileage tolls.[13] If vehicle fuel economy were initially greater, the optimum gasoline tax rises as each gallon of gasoline is associated with a larger reduction in auto and microbus mileage, which magnifies the congestion benefits. On the other hand, higher initial fuel economy moderately lowers optimal mileage tolls because there is less fuel and pollution saved per unit reduction in mileage. Finally, results are only moderately sensitive to varying the fraction of reduced travel demand in response to pricing one mode that comes from reduced overall travel demand, as opposed to substitution across different modes.

5. Conclusion

In principle, our results might appear to support a large increase in gasoline taxes for Mexico City. In practice, however, this may not be a very realistic policy to the extent that people could evade high fuel taxes in the metropolitan area by driving to fill up their tanks in a neighboring region with lower taxes or by smuggling low-tax fuel into Mexico City. But an important point is that more moderate fuel tax increases produce a large portion of the estimated welfare gains from far more dramatic tax increases.

Moreover, the most important source of efficiency gains under higher fuel taxes comes from reduced road congestion. However, a far more efficient and direct way to reduce road congestion is to impose a mileage toll on auto travel. Although much higher tolls are, in

[13] Varying the absolute values of the gasoline and mileage elasticities by the same proportion essentially has no effect on optimal taxes, as can be inferred from equations (10)–(12).

principle, warranted, a more moderate toll of around 6 cents per vehicle mile would still capture three-quarters of the potential welfare gains from a much larger toll. How might this policy be implemented?

Imposing a tax on the annual odometer mileage of vehicles registered in Mexico City would not make sense because it would penalize any driving outside the city (on roads that are far less congested) and would encourage use of vehicles within Mexico City that are not registered or are registered elsewhere.

Another option is a cordon toll, as recently implemented in London and Stockholm. In the London scheme (Leape 2006), tag plates are photographed at all entry points into the priced area, and charges are automatically debited from the vehicle owners' prepaid accounts (large fines are imposed for those who have not paid ahead of time). A worry with these schemes is that they may worsen congestion outside the priced area if people alter driving habits to avoid the toll, though this does not appear to be a serious problem in London and Stockholm.

A third option is to charge by the mile for any driving in Mexico City through global positioning systems or other electronic tolling, such as transponders embedded in roads that record vehicles as they pass. Most likely, mandating installation of the required metering technologies in vehicles would not work, given the large incentives for people to evade the mandate to avoid paying tolls. However, it might be possible to design schemes that get around this problem. For example, owners of vehicles with the required metering technology might be eligible for a lump-sum annual subsidy (financed in part by the new toll revenues). This subsidy could be set initially so that a large portion of drivers (those with lower-than-average annual mileage) gain by installing the technology (i.e., the subsidy payment exceeds their expected annual per mile charges). As the share of vehicles on the road that do not have metering technology progressively declines over time, it might become more feasible to phase in technology mandates for those remaining vehicles, to bring them into the pricing regime.[14]

And in principle, microbuses should also be tolled. Indeed, the welfare gains from microbus tolls would be larger if they were imposed in tandem with auto tolls, since this lowers efficiency losses from the potential substitution from microbus to auto. Finally, although our

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[14] A potential problem here is that the subsidy may increase vehicle ownership to the extent it exceeds the amount drivers are paying toward the new toll. Other taxes on vehicle ownership (applied to all vehicles) may have to rise to offset this effect.

treatment of public bus and rail is highly rudimentary, our results do at least suggest that any welfare gains from reforming fares for these transit modes are likely modest compared with the far larger gains from reforming auto taxation.

References

Bell, M.L., D.L. Davis, N. Gouveia, V.H. Borja-Aburto, and L.A. Cifuentes. 2006. "The Avoidable Health Effects of Air Pollution in Three Latin American Cities: Santiago, Sao Paulo, and Mexico City." *Environmental Research* 100: 431–40.

Borja-Aburto, V.H., D. Loomis, S.I. Bangdiwala, C.M. Shy, and R.A. Rascon-Pacheco. 1997. "Ozone, Suspended Particulates, and Daily Mortality in Mexico City." *American Journal of Epidemiology* 145: 258–268.

Bovenberg, A.L., and L.H. Goulder. 2002. "Environmental Taxation and Regulation," in *Handbook of Public Economics,* edited by A. Auerbach and M. Feldstein. New York: North Holland.

Bureau of Transportation Statistics (BTS). 2004. *National Transportation Statistics 2004*. Washington, DC: U.S. Department of Transportation.

Burtraw, D., A.J. Krupnick, E. Mansur, D. Austin, and D. Farrell. 1998. "The Costs and Benefits of Reducing Air Pollutants Related to Acid Rain." *Contemporary Economic Policy* 16: 379–400.

Davis, L.W. 2007. "The Effect of Driving Restrictions on Air Quality in Mexico City." Discussion paper. Department of Economics, University of Michigan.

De Borger, B., and S. Proost. 2001. *Reforming Transportation Pricing in the European Union: A Modelling Approach*. Northampton, MA: Edward Elgar.

Eskeland, G.S. 1992. "Attacking Air Pollution in Mexico City." *Finance and Development* 29: 28–30.

Eskeland, G.S., and T. Feyzioglu. 1995. "Rationing Can Backfire: The 'Day without a Car' in Mexico." Policy Research Working Paper 1554. Washington, DC: World Bank.

Eskeland, G.S., T.N. Feyzioglu, and DEC. 1994. "Is Demand for Polluting Goods Manageable? An Econometric Study of Car Ownership and Use in Mexico." Policy Research Working Paper Series 1309. Washington, DC: World Bank.

Federal Highway Administration (FHWA). 2000. *Addendum to the 1997 Federal Highway Cost Allocation Study Final Report*. Washington, DC: U.S. Department of Transportation.

Glaister, S., and D. Graham. 2002. "The Demand for Automobile Fuel: A Survey of Elasticities." *Journal of Transport Economics and Policy* 36: 1–25.

Goodwin, P.B. 1992. "A Review of New Demand Elasticities with Special Reference to Short and Long Run Effects of Price Changes." *Journal of Transport Economics and Policy* 26: 155–69.

Goodwin, P.B., J. Dargay, and M. Hanly. 2004. "Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review." *Transport Reviews* 24: 275–92.

Harrington, W. 1997. "Fuel Economy and Motor Vehicle Emissions." *Journal of Environmental Economics and Management* 33: 240–52.

Institutto Nacional de Ecologia (INE). 2003. *The Local Benefits of Global Air Pollution Control in Mexico City*., Mexico.

International Association of Public Transport (IAPT). 2007. *Millennium Cities Database for Sustainable Transport*. Brussels.

International Energy Agency (IEA). 2006. *Energy Prices and Taxes*. Paris.

International Monetary Fund (IMF). 2007. *International Monetary and Financial Statistics*. Washington, DC.

Kraus, M. 1991. "Discomfort Externalities and Marginal Cost Transit Fares." *Journal of Urban Economics* 29: 249–59.

Lago, A.M., P.D. Mayworm, and J.M. McEnroe. 1981. "Further Evidence on Aggregate and Disaggregate Transit Fare Elasticities." *Transportation Research Record* 799: 42–47.

Leape, J. 2006. "The London Congestion Charge." *Journal of Economic Perspectives* 20: 157–76.

Mayeres, I., and S. Proost. 2001. "Should Diesel Cars in Europe Be Discouraged?" *Regional Science and Urban Economics* 31: 453–70.

Mohring, H. 1972. "Optimization and Scale Economies in Urban Bus Transportation." *American Economic Review* 62: 591–604.

Molina, L.T., and M.J. Molina. 2002. *Air Quality in the Mexico Megacity: An Integrated Assessment*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Nordhaus, W.D. 2007. "A Review of the Stern Review on the Economics of Climate Change." *Journal of Economic Literature* XLV 686–702.

Nordhaus, W.D., and J. Boyer. 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.

O'Neill, M.S., D. Loomis, and V.H. Borja-Aburto. 2004. "Ozone, Area Social Conditions, and Mortality in Mexico City." *Environmental Research* 94: 234–42.

O'Ryan, R., and L. Larraguibel. 2000. Contaminacio´ n del aire en Santiago: estado actual y soluciones. Documento de Tranbajo CEA No. 75. Universidad de Chile.

Parry, I.W.H., and K.A. Small. 2005. “Does Britain or the United States Have the Right Gasoline Tax?” *American Economic Review* 95: 1276–89.

———. 2008. “Should Urban Transit Subsidies Be Reduced?” *American Economic Review*, forthcoming.

Parry, I.W.H., M. Walls, and W. Harrington. 2007. “Automobile Externalities and Policies.” *Journal of Economic Literature* XLV: 374–400.

Pratt, R.H., Texas Transportation Institute, Cambridge Systematics, Parsons Brinkerhoff Quade & Douglas, SG Associates, and McCollom Management Consulting. 2000. *Traveler Response to Transportation System Changes: Interim Handbook.* Transportation Research Board, Transit Cooperative Research Program Web Document 12 (March).

Safirova, E.A., S. Houde, and W. Harrington. 2008. “Marginal Social Cost Pricing on a Transportation Network: Comparison of Second-Best Policies.” Discussion paper 07-52. Washington, DC: Resources for the Future.

Sánchez, S. 2000. *Air Quality Management Programs in the MCMA: Overview and Assessment*. Report of the Third Workshop on Mexico City Air Quality, Cuernavaca, Mexico. MIT Integrated Program on Urban, Regional and Global Air Pollution Report No. 6. Cambridge, MA.

Small, K.A. 1992. *Urban Transportation Economics*. Fundamentals of Pure and Applied Economics, vol. 51. Chur, Switzerland: Harwood Academic Press.

Small, K.A., and C. Kazimi. 1995. “On the Costs of Air Pollution from Motor Vehicles.” *Journal of Transport Economics and Policy* 29: 7–32.

Small, K.A., and K. Van Dender. 2006. “Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect.” *Energy Journal* 28: 25–52.

Small, K.A., and E.T. Verhoef. 2007. *The Economics of Urban Transportation*. New York: Routledge.

Stern, N. 2007. *The Economics of Climate Change*. Cambridge: Cambridge University Press.

Tol, R.S.J. 2007. “The Social Cost of Carbon: Trends, Outliers and Catastrophes.” Economics discussion papers No. 2007-44. Kiel Institute for the World Economy.

U.S. Department of Energy (DOE). 1996. *Policies and Measures for Reducing Energy Related Greenhouse Gas Emissions: Lessons from Recent Literature*. Report No. DOE/PO-0047. Washington, DC: DOE Office of Policy and International Affairs.

Viscusi, W.K., and J.E. Aldy. 2003. “The Value of a Statistical Life: A Critical Review of Market Estimates throughout the World.” *Journal of Risk and Uncertainty* 27: 5–76.

Weitzman, M.L. 2008. “On Modeling and Interpreting the Economics of Catastrophic Climate Change.” Discussion paper. Department of Economics, Harvard University.

West, J.J., P. Osnaya, I. Laguna, J. Martinez, and A. Fernández. 2003. “Co-Control of Urban Air Pollutants and Greenhouse Gases in Mexico City.” Final report to U.S. National Renewable Energy Laboratory, subcontract ADC-2-32409-01.

West, S., and R.C. Williams. 2007. “Optimal Taxation and Cross-Price Effects on Labor Supply: Estimates of the Optimal Gas Tax.” *Journal of Public Economics* 91: 593–617.

Willig, R.D. 1976. “Consumer’s Surplus without Apology.” *American Economic Review* 66: 589–97.

World Bank. 2002a. *Cities on the Move: A World Bank Urban Transport Strategy Review*. Washington, DC.

———. 2002b. “Improving Air Quality in Metropolitan Mexico City: An Economic Valuation.” Policy research working paper WPS 2785. Washington, DC.

Appendix A: Analytical Derivations

Deriving Equation (9). From (1) and (4), the household's indirect utility function, *V*, is defined by

(A1) $$V(\bar{t}^{A}, \bar{t}^{MB}, \bar{t}^{B}, \overline{E}, \overline{GOV}, p^{G}, \delta^{A}, p^{MB}, p^{B}, p^{R})$$

$$= \underbrace{Max}_{X, M^{A}, M^{MB}, M^{B}, M^{R}} \quad u(X, M(M^{A}, M^{MB}, M^{B}, M^{R}), \sum_{i} \bar{t}^{i} M^{i}, \overline{E})$$

$$+ \lambda \left\{ I + \overline{GOV} - p^{G} F^{A} - K^{A} - \delta^{A} M^{A} - \sum_{i \neq A} p^{i} M^{i} - X \right\}$$

where $\lambda = u_X$ is the marginal utility of consumption. The solution to this problem yields the demand functions,

(A2) $$M^{A} = M^{A}(\bar{t}^{A}, \bar{t}^{MB}, \bar{t}^{B}, \overline{E}, \overline{GOV}, p^{G}, \delta^{A}, p^{MB}, p^{B}, p^{R})$$

and so on for other travel demands and the general good.

Partially differentiating the indirect utility function gives

(A3) $$V_{\bar{t}^{i}} = u_T M^{i},\ i = A, MB, B, R; \quad V_{\overline{E}} = u_{\overline{E}}; \quad V_{\overline{GOV}} = u_X; \quad V_{p^{G}} = -u_X F^{A};$$
$$V_{\delta^{A}} = -u_X M^{A}; \quad V_{p^{i}} = -u_X M^{i},\ i = A, MB, B, R$$

Totally differentiating the indirect utility function with respect to δ^{G}, using (A3), gives

(A4) $$\frac{1}{u_X}\frac{dV}{d\delta^{G}} = \frac{u_T}{u_X}\sum_{i=A,MB,B}\frac{d\bar{t}^{i}}{d\delta^{G}}M^{i} + \frac{u_{\overline{E}}}{u_X}\frac{d\overline{E}}{d\delta^{G}} + \frac{d\overline{GOV}}{d\delta^{G}} - F^{A} - M^{MB}\frac{dp^{MB}}{d\delta^{G}}$$

From differentiating (6a),

(A5) $$\frac{dt^{A}}{d\delta^{G}} = t^{A}_{\tilde{M}}\left(\frac{dM^{A}}{d\delta^{G}} + \beta^{MB}\frac{dM^{MB}}{d\delta^{G}} + \beta^{B}\frac{dM^{B}}{d\delta^{G}}\right)$$

and so on for increases in per unit travel times for microbus and public bus.

From differentiating (7),

(A6) $$\frac{d\overline{E}}{d\delta^{G}} = \overline{E}_{F^{G}}\frac{dF^{G}}{d\delta^{G}} + \overline{E}_{M^{A}}\frac{dM^{A}}{d\delta^{G}} + \overline{E}_{M^{MB}}\frac{dM^{MB}}{d\delta^{G}} + \overline{E}_{M^{B}}\frac{dM^{B}}{d\delta^{G}}$$

From differentiating (8a),

$$\text{(A7)} \qquad \frac{d\overline{GOV}}{d\delta^G} = F^G + \delta^G \frac{dF^G}{d\delta^G} + \sum_i \delta^i \frac{dM^i}{d\delta^G}$$

From differentiating (3),

$$\text{(A8)} \qquad \frac{dp^{MB}}{d\delta^G} = \frac{F^{MB}}{M^{MB}}$$

Substituting (A5)–(A8) into (A4) and collecting terms give expressions in (9).

Deriving (11). Totally differentiating the indirect utility function in (A1) with respect to δ^A and using (A3) give

$$\text{(A9)} \qquad \frac{1}{u_X}\frac{dV}{d\delta^A} = \frac{u_T}{u_X}\sum_{i=A,MB,B}\frac{d\bar{t}^i}{d\delta^A}M^i + \frac{u_{\bar{E}}}{u_X}\frac{d\bar{E}}{d\delta^A} + \frac{d\overline{GOV}}{d\delta^A} - M^A$$

Following the same steps as above, we obtain the analogous expression to that in equations (9a and b):

$$\text{(A10)} \qquad \frac{1}{u_X}\frac{dV}{d\delta^A} = (\delta^G - E^G)\frac{dF^G}{d\delta^A} + (\delta^A - E^A)\frac{dM^A}{d\delta^A} + (\delta^{MB} - E^{MB})\frac{dM^{MB}}{d\delta^A}$$

$$+ (\delta^B - E^B)\frac{dM^B}{d\delta^A} + \delta^R \frac{dM^R}{d\delta^A}$$

Equating this expression to zero gives the optimal toll in (11a–c).

Deriving (12) and (13). The derivations of (12a–c) and (13a–c) are analogous to that for (11) above.

Deriving (18). From (9a and b) and (10c), the welfare change from an incremental increase in the gasoline tax is

$$\text{(A11)} \qquad \frac{1}{u_X}\frac{du}{d\delta^G} =$$

$$\left\{E^G - \delta^G + (E^A - \delta^A)\rho_{AG} + (E^{MB} - \delta^{MB})\rho_{MBG} + (E^B - \delta^B)\rho_{BG} - \delta^R\rho_{RG}\right\}\left(-\frac{dF^G}{d\delta^G}\right)$$

Substituting δ^{G*} from (10a) gives (18a). Similarly, (18b) is obtained from (A10), (11a and c).

Appendix B: Details on Parameter Calculations and Data Sources

Basic mileage, travel speed, and fuel data. All the data on passenger miles, vehicle miles, average vehicle speeds, and fuel use across the four travel modes come from IAPT (2007). These data are for year 2005, just after the introduction of dedicated express bus lanes on the main north-south arterial route (which significantly reduced the number of microbuses). Data on auto vehicle miles include 1,695 miles by private passenger car, 264 vehicle miles by ordinary taxi, and 337 vehicle miles by shared taxi. Data are available on passenger miles by auto but not by taxi. To obtain passenger miles for taxi, we assume that the ordinary taxi carries on average 1.5 passengers and a shared taxi carries 2.5 passengers.

Fuel prices and taxes. These data are taken from IEA (2006, 198). Prices and taxes per gallon are for year 2005. The tax includes only the excise tax, not the value-added tax, since the latter applies to goods in general (rather than just to gasoline) and therefore does not raise the price of gasoline relative to other goods.

Marginal local pollution damages. We use various sources to infer a value for marginal pollution damages.

First, a widely cited study by Small and Kazimi (1995) put the damages from gasoline vehicles at 4 cents per mile, or 80 cents per gallon of gasoline, for 1992 in year 2000 dollars; this was for Los Angeles, where, as in Mexico City, meteorological and geographical characteristics are especially favorable to pollution formation.[15] Damage estimates are easily dominated by mortality risks. We divide this figure by 4 to account for the lower value of statistical life (and therefore lower value of health risks) in Mexico City, where per capita income is about one-fourth that in the United States.[16] Population density in Mexico City is about six times that in Los Angeles (Molina and Molina 2002, Table 2.1). On the other hand, the population of Mexico City is younger, and the average person might be less vulnerable to pollution-induced illness. For example, the proportion of Mexico City's population that is over 65 and most at risk is half that in the United States (Molina and Molina 2002, Table 4.1), although it is possible that younger people have a higher willingness to pay to avoid mortality risk. We scale up the damage

[15] Small and Van Dender (2006, 104) put pollution damages at 30 cents per gallon for U.S. urban areas in 2005. This lower figure mainly reflects the progressive tightening of emissions standards on new vehicles.

[16] Studies suggest that the elasticity of the value of life with respect to income is unity or less (Viscusi and Aldy 2003).

estimate by 4 to make some allowance for (sensitivity-adjusted) population exposure to pollution.[17] Thus, we are left with a damage estimate of 80 cents per gallon.

Second, a study by Bell et al. (2006) quantifies the health benefits from improving air quality in three Latin American cities, including Mexico City, based on pooling a variety of epidemiological evidence for both the United States and Mexico City, as well as evidence on the willingness to pay to avoid health risks. We consider only their mortality effects. In their baseline case in 2020, the benefits of reduced mortality (valued by willingness to pay) from a reduction in pollution concentrations of 14 percent in Mexico City amount to about $66 per capita per year in current dollars (this assumes a population of 26 million in 2020 and baseline pollution concentrations 40 percent greater than present levels).[18] A reduction in gasoline demand of 35 percent, or 52 gallons per capita, would reduce particulate concentrations (the most important pollutant from a health perspective) by 14 percent, given that gasoline accounts for roughly 40 percent of particulate concentrations in the region, mainly through secondary pollutant formation (O'Ryan and Larraguibel 2000). Thus, the benefit per gallon reduction is $1.26.

Erring slightly on the conservative side, we adopt a value of 90 cents per gallon of gasoline as a compromise between the above two figures.

We assume that the pollution damage per gallon of diesel fuel is the same as that for gasoline. Although the mix of local pollutants caused by combustion of the two fuels is somewhat different, estimates of the damages per gallon from diesel fuel combustion are roughly comparable to those for gasoline, at least for the United States (FHWA 2000).[19] The pollution cost for diesel is expressed on a per passenger mile basis for public bus by multiplying by bus fuel economy and dividing by bus occupancy.

Marginal global pollution damages. Most studies that attempt to quantify the damages from CO_2 emissions and consequent future global climate change (see the exhaustive list of studies in Tol 2007) place estimates somewhere between about $5 and $20 per ton of CO_2. There is little consistency among the estimates, however; in some, catastrophic risks are the dominant damage, while in others, it is either

[17] Because the Mexico City basin is much smaller, a given amount of auto emissions becomes more concentrated in the air than in Los Angeles. Some further adjustment would be required if total pollution damages were convex in ambient concentrations (i.e., marginal damages were an increasing function of concentrations). However, available evidence suggests that aggregate mortality risks among a given population are roughly linear in ambient concentrations (e.g., Burtraw et al. 1998).

[18] The estimate is broadly similar to that in World Bank (2002b), where the benefits from a 10 percent reduction in pollution concentrations amount to about $44 per capita per year.

[19] Mayeres and Proost (2001) assume that per gallon pollution costs are larger for diesel than for gasoline (though this depends strongly on local pollution control policies). Our results are only moderately affected by different assumptions about diesel fuel damages.

market impacts like agricultural damage, or nonmarket impacts like human health from the spread of tropical disease. Nordhaus and Boyer (2000) provide the most comprehensive estimate, and their central value (after updating in Nordhaus 2007) is $8 per ton. Stern (2007) obtains a central damage estimate of $85 per ton of CO_2, because he uses a much lower discount rate—specifically, zero discounting of future utility—than the market discount rate assumed in Nordhaus (2007). Although the choice of discount rate is highly contentious, we ourselves are somewhat uncomfortable with zero discounting of future utility because of its perverse implications; for example, it implies that every previous generation should have been made worse off to make the current generation better off. Weitzman (2008) takes a different perspective on catastrophic damages than in other studies. He shows that under a plausible utility function, marginal damages from CO_2 emissions can become infinitely large if there is a small probability of truly catastrophic climate change that could permanently reduce world consumption by 99 percent. Clearly, the appropriate value to place on CO_2 is much disputed. We adopt a benchmark value of $10 per ton and illustrate the implications of other assumptions in the sensitivity analysis.

A gallon of gasoline and a gallon of diesel contain 0.0024 and 0.0028 tons of carbon, respectively (http://bioenergy.ornl.gov/papers/misc/energy_conv.html). Combustion of these two fuels produces about 0.009 and 0.0011 tons of CO_2, respectively. Thus, our benchmark damage assumption amounts to about 9 per gallon of gasoline and 11 cents for diesel. Again, pollution costs for diesel are converted to costs per passenger mile by public bus.

Congestion costs. We are not aware of a direct estimate of the marginal cost of traffic congestion for Mexico City (averaged across different routes and time of day). In fact, there are not that many estimates even for major urban areas in the United States. We therefore adopt the following procedure.

We assume a free-flowing auto speed of 30 mph, so the time per mile if roads were uncongested, α in equation (15), would be 0.033 hours per mile. The actual time to drive an auto mile in Mexico City, the inverse of the current auto speed (14.3 mph), is 0.070 hours per mile (IAPT 2007), implying a delay per mile of 0.037. Plugging these values into (15), with $\widetilde{M} = M^0$, gives γ= 1.121.

The gross hourly wage rate for Mexico City is taken to be $4 (IMF 2007). Following U.S. studies (see the review in Small and Verhoef 2007), we assume the value of travel time is half the hourly wage. This gives a monetized marginal congestion cost of 27.1 cents per vehicle mile, or 18.5 cents per passenger mile.

Passenger car equivalents. We assume the same value for the passenger car equivalent for an extra *vehicle* mile by public bus as used by Parry and Small (2008) for London, namely 5. And for microbuses we assume the passenger car equivalent for an extra *vehicle* mile is 3. Diving by vehicle occupancy gives the passenger car equivalents in passenger miles.

Marginal accident cost. Parry and Small (2005) put the marginal external costs of traffic accidents at 3 cents per vehicle mile, averaged across driving in the United States. This mainly reflects the costs of fatal and nonfatal injury risks (that are not internalized by drivers), property damage to vehicles, and medical costs. We make two adjustments to this U.S. estimate. First, we divide by 4 to account for the lower value of injuries and property values in Mexico City with its lower per capita income. Second, to make some allowance for differences in crash rates and vehicle safety, we multiply by the ratio of fatalities per vehicle mile in Mexico City relative to that in the United States, where this ratio is (38/15).[20] This gives 1.9 cents per vehicle mile, or 1.2 cents per passenger mile.

For microbus and public bus, accidents costs per vehicle mile are taken to be the same as for auto. Buses have much greater weight and therefore are far more lethal to other road users in a collision for a given vehicle speed. However, they drive more slowly (thereby reducing the severity of any given accident) and they are driven by professionals. For comparison, a study by FHWA (1997) put marginal external accident costs per vehicle mile for single and combination trucks at roughly the same as those for autos.

Fuel price elasticities. The empirical literature on gasoline price elasticities for advanced industrial countries, especially the United States, is large. Surveys by Goodwin et al. (2004) and Glaister and Graham (2002) put the long-run elasticity at around –0.6 to –0.7, while assessments by U.S. DOE (1996) and Small and Van Dender (2006) suggest an elasticity of around –0.4. Typically, about a half to two-thirds of the elasticity comes from long-run improvements in vehicle fuel economy, and the remainder from reduced vehicle use. We are aware of only one study that uses Mexican data. Eskeland and Feyzioglu (1994) put the gasoline demand elasticity at –0.8, using panel data from 31 Mexican states. We might expect a somewhat larger mileage–fuel price response for Mexico City, given the wider availability of transit alternatives to private car use. We adopt a benchmark value of –0.6 for the gasoline price elasticity, with the assumed response split equally between better fuel economy and reduced mileage. For the benchmark case, we assume that mileage–fuel price and fuel economy–fuel price elasticities are the same for autos and microbuses.

[20] Statistics are from IAPT (2007) and BTS (2004, Table 2.17) and are expressed in deaths per billion vehicle miles of travel.

There is a potential problem with applying evidence based on nationwide fuel demand responses to a fuel tax increase that is specific to one region (see also the discussion in Section 5). If fuel taxes are increased substantially in Mexico City but not in neighboring regions, people might be induced to drive to lower-price regions for refueling (or smuggle gasoline into Mexico City). We do not have evidence on how this effect might increase the overall magnitude of the region-specific fuel price elasticity. This is another reason for being cautious about the welfare effects from the large fuel price increases considered above.

Public bus and rail mileage elasticities. Again, a substantial body of empirical work addresses the behavioral response of public bus and rail passengers to higher fares, though it mostly applies to the United States. However, we see no obvious reason why these estimates would overstate or understate behavioral responses for Mexico City. Therefore, based on Lago et al. (1981), Goodwin (1992), and Pratt et al. (2000), we assume that the own-fare demand elasticity is -0.5 for bus and -0.3 for rail.

Relative price coefficients. Suppose, for the moment, that there were no microbuses and only autos used gasoline. Then the reduction in auto mileage per gallon reduction in gasoline would simply equal auto fuel economy (miles per gallon) times the fraction of the reduction in gasoline use that comes from reduced miles, as opposed to improved fuel economy, which is 0.5 (Parry and Small 2005). Since some gasoline is used for microbuses, we scale this back by the fraction of gasoline used for autos (0.88) to obtain ρ_{AG} = .44 times auto fuel economy. Conversely, ρ_{MBG} = 0.06 (= 0.5 × 0.12) times microbus fuel economy.

Assumptions about how passengers reallocate among other modes in response to higher prices for one mode are described in the main text.

Initial transit fares and operating costs. Currently, the subway carries 4.4 million trips every day, and the fare per subway trip is 20 cents (from http://wikitravel.org/en/Mexico_City, accessed February 2008). According to the World Bank (2002a, Table 8.3), the fare in 2000 was 15 cents. For 2005, we assume the fare was 18 cents and passenger trips were 4.2 million, hence assumed annual revenue is $321 million. Dividing by total passenger miles by rail, 427 per capita times the population of 18 million gives a fare per passenger mile of 4 cents. We assume the revenue to operating cost ratio for rail in 2005 was the same as in 2000, which was 53 percent (World Bank 2002a, Table 8.3). Therefore, average operating costs per passenger mile are 7.5 cents or, multiplying by passenger occupancy, $13 per vehicle mile. For the Washington and Los Angeles rail systems, Parry and Small (2008) put the average operating cost per vehicle mile at around $50. Roughly speaking these figures seem consistent, given that wages (the main component of operating costs) are four times greater on average in the United States. Following Parry and Small (2008) we assume that 10 percent of average operating costs for rail reflect fixed costs; therefore, the marginal operating cost is 6.8 cents per passenger mile, or $11.7 per vehicle mile.

For microbus, fares are approximately 1 peso per km for trips less than 3 km and 0.3 pesos per km for longer trips (http://wikitravel.org/en/Mexico_City). We assume the initial fare is 0.7 pesos per km, or 6 cents per mile.

We were unable to find direct estimates of fare revenues and operating costs from the public bus company for Mexico City and we therefore extrapolate these values. We assume the fares per mile for public bus and microbus are the same. As for average operating costs per vehicle mile, Parry and Small (2008) compute them for bus at about one-quarter those for rail. Applying the same ratio, operating costs for bus would be $3.25 per vehicle mile for Mexico City, or 10.5 cents per passenger mile.

Figure 1. Welfare Gain from Raising the Gasoline Tax

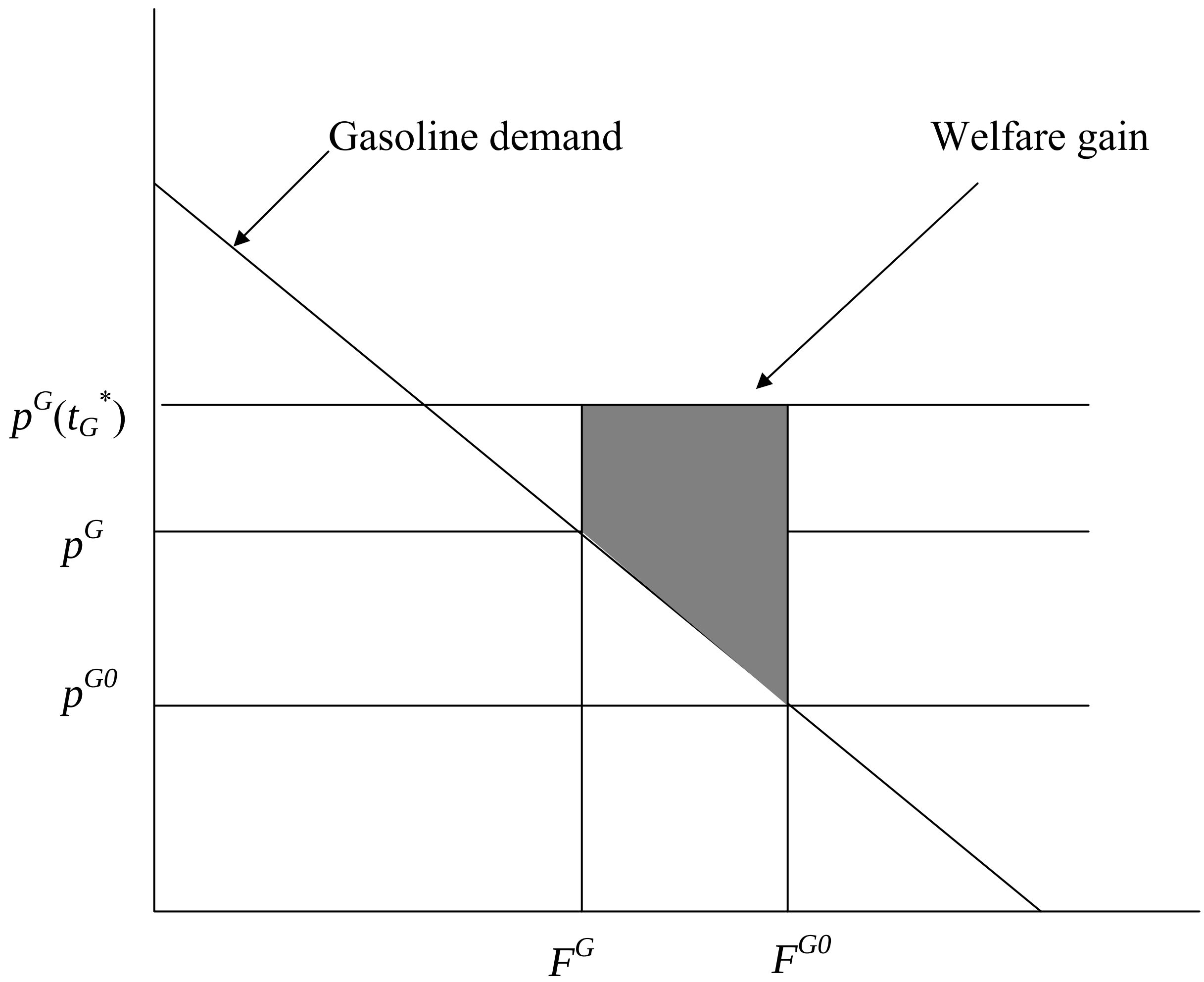

Table 1. Ranking of Selected Megacities Based on Ambient Air Quality and Road Travel Speed

Megacities in 2000	TSP ($\mu g\ m^{-3}$) [Rank]	SO_2 ($\mu g\ m^{-3}$) [Rank]	NO_2 ($\mu g\ m^{-3}$) [Rank]	MPI [Rank]	average mph [Rank]
Tokyo	40 [15]	19 [9]	55 [11]	-0.27 [16]	16.2 [9]
Mexico City	201 [10]	47 [4]	56 [10]	0.52 [10]	14.0 [6]
New York - Newark	27 [18]	22 [7]	63 [7]	-0.23 [14]	23.9 [14]
São Paulo	53 [14]	18 [10]	47 [12]	-0.29 [17]	15.0 [8]
Mumbai (Bombay)	243 [9]	19 [9]	43 [14]	0.39 [11]	13.8 [5]
Kolkata (Calcutta)	312 [6]	19 [9]	37 [15]	0.59 [9]	na
Shanghai	246 [8]	53 [3]	73 [5]	0.87 [8]	12.4 [4]
Buenos Aires	185 [11]	20 [8]	20 [18]	-0.01 [13]	18.6 [10]
Delhi	405 [4]	18 [10]	36 [16]	0.92 [7]	14.4 [7]
Los Angeles - Long Beach - Santa Ana	39 [16]	9 [13]	66 [6]	-0.25 [15]	29.5 [15]
Osaka - Kobe	34 [17]	19 [9]	45 [13]	-0.37 [18]	20.5 [13]
Jakarta	271 [7]	35 [6]	120 [3]	1.24 [5]	11.6 [2]
Beijing	377 [5]	90 [2]	122 [2]	2.01 [2]	11.1 [1]
Rio de Janeiro	139 [13]	15 [11]	60 [8]	0.11 [12]	18.6 [10]
Cairo	593 [2]	37 [5]	59 [9]	1.93 [3]	12.4 [3]
Dhaka	516 [3]	120 [1]	83 [4]	2.40 [1]	na
Moscow	150 [12]	15 [11]	170 [1]	1.07 [6]	18.6 [10]
Karachi	668 [1]	13 [12]	30 [17]	1.81 [4]	na

Notes
Pollution figures are for year 2000, while road speed is for 2005. Road speed is miles per hour averaged across all passenger vehicles.
TSP is total suspended particulates. $\mu g\ m^{-3}$ is micrograms per cubic meter. And MPI is a multi-pollutant index combining all three pollutants.

Source: Gurjar et al. (2007) and IATP (2007).

Table 2. Selected Parameter Asumptions for the Baseline Simulations
(expressed in US $, year 2005 or thereabouts)

	Mileage parameters				
	Auto	Minibus	Bus	Rail	Total or average
Annual passenger miles per capita	3,723	1,067	371	427	5,588
Annual vehicle miles per capita	2,296	139	12	2	2,449
Average vehicle speed, mph	14.3	10.5	11.4	20.5	14.1
Average vehicle occupany	1.6	8	31	174	2.3
Current fares or tolls, cents per passenger mile	na	6.0	6.0	4.0	
Marginal operating cost, cents per passenger mile	na	6.0	10.5	6.8	
Vehicle miles per gallon	17.4	7.8	4.3		16.8
Passenger miles per gallon	28.3	60.1	131.6		39.1
Marginal external costs					
Congestion, cents per vehicle mile	27	81	136	0	30.7
Congestion, cents per passenger mile	17	11	4	0	13.4
Accidents, cents per vehicle mile	1.9	1.9	1.9	0	1.9
Accidents, cents per passenger mile	1.2	0.2	0.1	0	0.8
total, cents per passenger mile	17.9	10.8	4.5	0	14.3
local and global pollution, cents per passenger mile	3.5	1.5	0.8	0	2.7
total external cost, cents per passenger mile	21.4	12.3	5.2	0	17.0
Mileage elastcities					
own mileage elasticity wrt own fuel price or fare	-0.30	-0.30	-0.5	-0.3	
Relative price coefficients for mileage					
Fraction of reduced auto travel going to mode	na	0.46	0.16	0.18	
Fraction of reduced microbus travel going to mode	0.35	na	0.16	0.19	
Fraction of reduced bus travel going to mode	0.35	0.25	na	0.10	
Fraction of reduced rail travel going to mode	0.35	0.26	0.09	na	
Fraction of reduced auto/microbus travel going to other mode	na	na	0.28	0.32	

	Gasoline parameters
Fuel use, gallons per capita	149.4
Current (effective) fuel tax, c/gal.	17
Retail price of fuel, c/gal.	221
External cost per gallon	
Local pollution, cents per gallon	90
Global pollution, cents per gallon	9
total	99
Own-price fuel elasticity	-0.60

Table 3. Optimal Gasoline Tax and Welfare Gains from Tax Reforms

Components	Optimal tax (cents per gallon)	Contribution to optimal tax (%)
Local pollution	90	33.1
Global pollution	9	3.3
Congestion for autos	131	48.3
Accidents for autos	18	6.8
Congestion/accidents for microbus	25	9.2
Substitution into other modes and fuels	-2	-0.7
Total	**272**	**100**

Effects of higher gasoline taxes	
increase gasoline tax by 50 cents	
% reduction in gasoline use	11.5
welfare gain, $ per capita	46.6
increase gasoline tax by $1	
% reduction in gasoline use	20.1
welfare gain, $ per capita	83.1
increase in gasoline tax to optimal level	
% reduction in gasoline use	36.9
welfare gain, $ per capita	131.8

Table 4. Optimal Auto Toll Per Vehicle Mile and Welfare Gains from Tax Reforms

	Optimal tax		
Componets	cents per vehicle mile	equivalent increase in gasoline tax cents per gallon	Contribution to optimal tax (%)
Local pollution	4.1	71	20.2
Global pollution	0.4	7	2.0
Prevailing fuel tax	-0.8	-13	-3.8
Congestion for autos	16.9	295	84.2
Accidents for autos	1.9	33	9.5
Substitution into microbus	-2.3	-40	-11.4
Substitution into other modes and fuels	0.1	-2	-0.6
Total	**20.3**	**350**	**100**

Effects of higher auto mileage tolls	
toll of 3 cents per vehicle mile	
% reduction in auto mileage	6.1
welfare gain, $ per capita	30
toll of 6 cents per vehicle mile	
% reduction in auto mileage	10.9
welfare gain, $ per capita	55
optimal per mile toll	
% reduction in auto mileage	24.8
welfare gain, $ per capita	109

Table 5. Optimal Microbus Toll per Vehicle Mile and Welfare Gains from Policy Reform

Componets	Optimal tax	
	cents per microbus mile	fuel tax equivalent (cents per gallon)
Local pollution	2.9	23
Global pollution	0.3	2
Prevailing fuel tax	-0.6	-4
Congestion and accidents for microbus	79.8	625
Substitution with auto	-46.2	-362
Substitution with other modes and fuels	-2	-16
Total	**34.2**	**267**
Effects of microbus subsidies		
toll of 6 cents per vehicle mile		
% decrease in microbus mileage	5.6	
welfare gain, $ per capita	2.8	
toll of 12 cents per vehicle mile		
% decrease in microbus mileage	10.1	
welfare gain, $ per capita	5.0	
optimum per mile toll		
% decrease in microbus mileage	21.2	
welfare gain, $ per capita	8.6	

Table 6. Optimal Fares for Public Bus and Rail

Componets	cents per passenger mile	
	public bus	rail
Marginal operating cost	10.5	6.8
Local and global pollution (own mode)	0.8	0
Accidents (own mode)	0.1	0
Ccongestion (own mode)	4.4	0
Substitution with auto	-7.3	-7.3
Substitution with other modes and fuels	-3.4	-4.1
Total	5.1	-4.6
Difference between optimum and current fare	-0.9	-8.6
Welfare gain		
From 1 cent change in fare towards optimum, $/capita	0.3	2.8

Table 7. Sensitivity of Optimal Taxes to Alternative Parameters

	Gasoline tax cents /gallon	Auto toll cents/vehicle mile	Micobus toll cents/vehicle mile
Baseline value	272	20.3	34.2
Pollution costs per gallon			
doubled	371	24.8	37.3
halved	222	18.1	32.6
Marginal congestion costs			
doubled	373	32.6	67.7
halved	213	12.4	17.0
Auto and microbus mileage/fuel price elasticity			
-0.45	337	20.3	34.2
-0.15	198	20.3	34.2
Initial auto and microbus fuel economy			
increased 25%	308	18.7	33.5
reduced 25%	234	22.0	35.3
Reduced overall travel demand			
increased 25%	273	20.5	39.9
reduced 25%	272	20.0	28.5