THE IMPACT OF POLICIES TO CONTROL MOTOR VEHICLE EMISSIONS IN MUMBAI, INDIA*

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ABSTRACT: This paper examines the impacts of measures to reduce emissions from buses, cars, and two-wheelers in Mumbai, India. We have considered three possible policies: conversion of diesel buses to CNG, an increase in the price of gasoline and a tax on vehicle ownership.

Our results suggest that the most effective policy to reduce emissions from passenger vehicles—in terms of the total number of tons of PM10 reduced—is to convert diesel buses to CNG. The conversion of 3,391 diesel buses to CNG would result in an emissions reduction of 663 tons of PM10 per year, 14 percent of total emissions from transport.

1. INTRODUCTION

Motivation and Purpose

Mumbai, like many Indian cities, has a serious air pollution problem caused, at least in part, by mobile sources. Between 2000 and 2002, annual average PM10 was approximately 80 μg/m3 (World Bank, 2005), higher than in Mexico City.[1] In many ways, however, Mumbai is more fortunate than other

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[1]The National Environmental Engineering Research Institute (NEERI) monitors RSPM (respirable particle) levels, which are approximately equivalent to PM10. It should be noted that annual average RSPM has been declining steadily since 1997, largely as a result of the closing of textile mills in the city.

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Indian cities. It has an extensive rail and bus system and a much smaller vehicle fleet than Delhi, a city of comparable size and income. The problem facing Mumbai is to reduce emissions from diesel trucks and buses, as well as taxis and auto-rickshaws—and to prevent rapid growth of the private vehicle fleet.[2]

In this paper, we examine the impacts of measures to reduce emissions from passenger transport; specifically, buses, cars and two-wheelers. These include the possibility of converting diesel buses to CNG, as the Indian Supreme Court required in Delhi, which would necessitate an increase in bus fares to cover the cost of pollution controls. We also consider raising the price of gasoline, which should affect the ownership and usage of cars and two-wheelers, as well as imposing a license fee on cars, to retard growth in car ownership. The impact of each policy on emissions depends not only on how the policy affects the mode that is regulated but also on shifts to other modes. For example, a "clean bus" policy might actually increase emissions from transport if the increase in bus fares causes enough people to switch to cars and two-wheelers.

Previous attempts to estimate the impacts of pollution control policies from passenger vehicles have focused primarily on controlling emissions from automobiles and relied mostly on U.S. data. A key result in this literature (Eskeland, 1994) is that a tax on auto emissions can be mimicked by combining command-and-control measures to reduce emissions per mile with a gasoline tax to reduce vehicle miles traveled. At the margin, the cost of emissions reductions should be the same via the gas tax and pollution controls. Holding the marginal cost of pollution controls constant, a higher percent of the total reduction in emissions will come from a tax on gasoline, the more elastic is the demand for gasoline. Using data from the U.S. Consumer Expenditure Survey, Fullerton and West (1999) calculate the welfare improvement from a zero-tax scenario to the ideal Pigouvian tax, and find that 71 percent of that gain can be achieved by the second-best combination of taxes on gas, engine size, and vintage. A gas tax alone attains 62 percent of the Pigouvian gain.

In countries where the share of ridership in public transit, in particular buses, is high, there is a need to evaluate the impacts of policies that reduce emissions from buses. These can take the form of reducing emissions from diesel buses—for example, by installing particle traps if lower-sulfur diesel fuel is available—or replacing diesel buses with CNG buses. Assuming that bus fares will rise to cover the cost of pollution control measures, a potential adverse effect of these policies may be the switch from public to private transportation, which is likely to entail higher emissions per passenger mile traveled. To our knowledge the only study that examines the effect of mode substitution on pollution control policies is Swait and Eskeland's (1995) study of mode

[2]Some measures along these lines have already been taken: by 2003 all highly polluting taxis and auto-rickshaws were required to be converted to natural gas. The sulfur content of diesel fuel has been reduced from 2500 to 500 ppm (World Bank, 2005).

choice in São Paolo. They examine the net effect on air pollution of subsidizing bus fares. We examine the related question of whether raising bus fares will, on net, cause substitution to dirtier forms of transport, per passenger mile traveled

Approach Taken

Estimating the impact of pollution control policies that affect the price of travel requires estimating models of mode choice and vehicle ownership. We use data from a survey of 5,000 households in Mumbai, conducted in 2003, to estimate models of commute mode choice and vehicle ownership. The price elasticities obtained from these models are combined with data on passenger-kilometers traveled and emissions per passenger kilometer to compute the impact of policies on emissions from transport. Specifically, we ask:

- How sensitive is private vehicle ownership to a change in purchase price or to a change in the price of gasoline?
- What would be the net effect of a change in the tax on gasoline on emissions from transport in Mumbai?
- How will the requirement that buses be converted to CNG affect bus ridership and vehicle ownership, assuming that it will increase bus fares?
- What would be the net effect on emissions from transport of a policy to convert diesel buses to CNG?

The paper is organized as follows. Section 2 presents a simple model of the generation of emissions from transport that clarifies the relationship between changes in prices, modal shares and emissions. It also presents the stylized facts about the vehicle fleet and emissions from transport in Mumbai. To estimate the impact of a change in, e.g., the price of gasoline on emissions from transport requires estimating the elasticity of vehicle ownership and usage with respect to the price of gasoline, as well as cross-price elasticities. The models of mode choice and vehicle ownership that we estimate are described in Section 3. Section 4 describes our data, and Section 5 our empirical results. We conclude by providing a rough calculation of the net benefits associated with a program to convert diesel buses to CNG in Mumbai.

2. THE IMPACT OF POLLUTION CONTROL POLICIES ON EMISSIONS FROM TRANSPORT

This section outlines the simple analytics of the impact of policies to control emissions from passenger vehicles on particulate emissions from transport. Let E be total particulate emissions from transport and E_c particulate emissions from commercial vehicles. Let x_i denote the aggregate demand for mode i (in passenger kilometers) and e_i particulate emissions per passenger kilometer associated with mode i. In practice, passenger modes include walking and rail, for which $e_i = 0$, as well as car, two-wheeler, and bus. Aggregate emissions from transport are given by (1)

$$E = E_c + \sum_i x_i e_i \tag{1}$$

Alternative Pollution Control Policies

With this simple framework, we can evaluate the impacts of policies aimed at reducing pollution. We consider two policies: an increase in the gasoline tax and the conversion of buses from diesel to CNG.

In practice, an increase in the tax on gasoline will primarily affect the cost of driving cars and two-wheelers.[3] If p_j denotes the cost of a car, per passenger kilometer traveled, and p_k the cost per passenger kilometer of a two-wheeler, then (assuming that p_j and p_k are proportional to the price of gasoline) the elasticity of emissions, E, with respect to a change in the price of gasoline is given by (2)

$$\frac{\partial E}{\partial p_{gas}} \frac{p_{gas}}{E} = \sum_i \frac{e_i x_i}{E} [\varepsilon_{ij} + \varepsilon_{ik}] \tag{2}$$

where ε_{ij} is the elasticity of total passenger kilometers for mode i (x_i) with respect to the price of mode j. Note that:

$$x_i = m_i \,^* \text{(average trip length)}_\text{i} \,^* \text{(total number of trips made by all travelers)}$$

where m_i = share of trips made via mode i. Assuming that a change in the price of gasoline has no effect on the total number of trips made, or on average trip length, the elasticity of x_i with respect to p_j is the elasticity of m_i with respect to p_j.[4]

Equation (2) implies that the net effect of a change in the price of gasoline is the sum of two effects: the decline in the share of trips made by cars and two-wheelers (the own-price elasticity effect) and the effect of an increase in the price of gasoline on shifts to other modes (e.g., walking, bus and rail). The net impact of these effects depends on the magnitude of cross-price elasticities of demand, as well as on how polluting substitute modes are.

To evaluate the impact of a policy to replace diesel buses with CNG buses, with an increase in bus fares to cover the cost of the conversions, let ^{0}'s denote emissions and passenger kilometers traveled before the program is enacted and

[3]As noted below, regulations are in effect to convert taxis and auto-rickshaws (three-wheelers) to CNG. We therefore focus on the impact of an increase in the price of gasoline on cars and two-wheelers (motorcycles and scooters).

[4]An increase in the price of gasoline should decrease average trip length and the number of trips made; however, our data do not permit us to estimate these effects. Our estimate of the elasticity of passenger kilometers traveled with respect to the price of gasoline is therefore an underestimate of the true elasticity.

[1]'s denote after-program values. The impact of the program on total emissions from transport is given by (3),

$$\Delta E = \left(e_i^0 x_i^0 - e_i^1 x_i^1\right) + \sum_{-i} e_{-i} \frac{\partial x_{-i}}{\partial P_i} \tag{3}$$

where i refers to "bus." Whether the net effect of the clean bus program is to reduce emissions from transport depends on whether an increase in the bus fare induces substitution to other, dirtier modes (per passenger kilometer), such as cars and two-wheelers.

The Contribution of Various Modes to Transport Emissions in Mumbai

Calculating the elasticity of emissions from transport with respect to a change in the price of gasoline or a "clean bus" policy requires estimates of the share of emissions attributable to each transport mode ($e_i x_i / E$). In this section we present the stylized facts about the vehicle fleet, vehicle kilometers traveled and the contributions of various types of vehicles to PM10 emissions in Mumbai.

Table 1 presents the 2001 vehicle fleet, estimates of the fraction of VKTs attributable to various segments of the fleet, and the emissions factors used by the National Environmental and Engineering Research Institute (NEERI) in calculating an emissions inventory for Mumbai (NEERI 2004). Two-wheelers and cars constitute three quarters of the vehicle fleet in Mumbai. According to the 2001 Census, 9 percent of all households own a two-wheeler, while 8 percent own a car. These percentages are much lower than in Delhi, where 28 percent of households own two-wheelers and 13 percent own cars.

The lower rate of vehicle ownership in part reflects Mumbai's extensive rail and bus systems. Mumbai is served by three rail lines, the Western, Central, and Harbor, which carry 5 million passengers per day. All trains are electric, and therefore do not contribute to PM emissions in the Greater Mumbai Region (GMR). Mumbai's municipal bus system, which carries 4.5 million passengers each day, is operated by the Brihanmumbai Electric Supply and Transport Undertaking (BEST). Of the 14,500 buses in Mumbai, approximately 3,400 are BEST buses. The remainders are school buses and buses that provide private commuting services. Taxis and auto-rickshaws (three-wheeled vehicles) comprise the remainder of Mumbai's passenger transport system.

Data on vehicle kilometers traveled come from studies conducted by NEERI (2004) to construct a grid-wise emissions inventory for Mumbai, as do the emissions factors listed in Table 1. Estimates of VKTs for each grid cell and vehicle type were constructed from vehicle counts, obtained at different times of day, and estimates of grid-wise road length. These, together with emissions factors, were used to estimate annual tons of PM10 emitted in each 2 km × 2 km grid in the city. The corresponding fraction of PM10 emissions accounted for by each vehicle class are obtained from the grid-wise emissions

TABLE 1: Share of Vehicle Usage and PM10 Emissions From Transport

	Two-wheeler	Three-wheeler	Car	Taxi	Best bus	Other diesel vehicles	Total
Number of vehicles (2001)	440,517	101,914	344,870	62,447	3,391	76,424	1,029,563
Share of Vehicle km (2002)	20%	16%	29%	14%	4%	17%	100%
NEERI Emission factors (g/km)	0.21	0.21	0.27	0.27	3	3	–
Share of PM10 (2002)	5%	4%	10%	5%	14%	63%	100%

inventory.[5] Table 1 indicates that, in 2002, diesel vehicles (buses and goods vehicles) contributed 76 percent of directly emitted PM10 from transport in Mumbai.[6] Private passenger vehicles (cars and two-wheelers) contributed 15 percent of directly emitted PM and taxis and three-wheelers about 9 percent of PM10 emissions.[7]

What is being done to control emissions from transport in Mumbai and what remains to be done? As of 2002, all new commercial and noncommercial vehicles must obey Euro II emissions standards. To deal with highly polluting, older vehicles, all taxis over 8 years old are either to be retired or converted to CNG (as of 1/1/2003), as are highly polluting three-wheelers over 8 years of age. All transport vehicles over 8 years old (except BEST buses) are to be retired or converted to CNG, effective 2/1/2004 (World Bank, 2005).

Policies that are not included in the above list are requirements to reduce emissions from BEST buses, most of which are diesel, and policies to restrict the ownership and use of cars and two-wheelers. BEST diesel buses could be replaced with CNG buses or diesel buses with diesel oxidation catalysts (DOCs). Vehicle ownership and use could be discouraged by imposing a significant license fee on automobiles; ownership and use could also be discouraged by raising the tax on gasoline. If these policies were implemented in 2005, we would expect the share of emissions from taxis and three-wheelers to differ from those in row 4 of Table 1, assuming that the policies to retire or convert old taxis and three-wheelers are enforced. For this reason, we treat the contribution of taxis and three-wheelers to PM emissions as negligible in computing the share of emissions from different categories of vehicles. This implies that BEST buses account for 15.4 percent, cars 10.6 percent, and two-wheelers 5.6 percent of the PM10 emissions from transport.

3. MODELS OF VEHICLE OWNERSHIP AND COMMUTE MODE CHOICE

Calculating the effect of the policies outlined above requires estimates of the price elasticity of demand for passenger transportation. In this section, we describe models of mode choice, which we estimate to produce short-run price elasticities of demand. In these models we treat the number, origin and destination of trips as fixed, and look at the impact of changes in the time and

[5]It should be noted that the existing distribution of emissions (NEERI, 2004, Fig. 3.7) reflects the decentralization of jobs and residences in the GMR, a phenomenon noted in the United States by Glaeser and Kahn (2003). The highest emission density occurs in zone 3 of city (see Baker et al., 2005 for a map). This reflects the northward movement of jobs from the old CBD (zone 1) to zones 2 and 3, as well as the movement of wealthy households to zone 4.

[6]According to Burningham (2005) BEST's 3,391 buses traveled approximately 240 million km in 2002–2003. Applying NEERI's emission factor of 3 gm/km to this mileage yields 720 tons of PM10 emissions.

[7]According to NEERI the share of PM10 from transport is 32 percent. It is 45 percent from industry, 18 percent from area sources, and 5 percent from building and road construction.

TABLE 2: Main Mode to work by Household Income (%)

	<5,000	5,000–7,500	7,500–10,000	10,000–20,000	>20,000	All HHs
On foot	61	50	41	30	15	44
Bicycle	6	4	2	1	0	3
Train	16	23	26	26	21	23
Public bus	15	17	18	16	13	16
Auto-rickshaw	1	1	1	3	3	2
Taxi	0	0	0	0	1	0
Own two-wheeler	1	4	10	18	21	9
Own car	0	0	0	4	24	3
Other's car	0	0	0	0	1	0
Other	0	1	1	0	3	1
Total	100	100	100	100	100	100

money costs of travel on mode choice. We also estimate joint models of vehicle ownership and mode choice.

Before presenting the models that we estimate, we examine mode choice in Mumbai. Tables 2 and 3 are based on a survey of 5,000 households in the Greater Mumbai Region conducted by Baker et al. (2005).[8] Table 2 shows the main commute mode[9] to work for the two most important income earners in each household who work at a fixed location within the GMR. Table 3 shows the main mode used for work and non-work trips, based on travel diaries administered to the main earner in the household, a randomly chosen adult in the household, and a randomly chosen person between 16 and 21.

Several points are worth emphasizing. The first is that work trips constitute almost half of all trips made by adults in Mumbai. Indeed, work trips constitute 67.5 percent of all trips when trips are weighted by distance traveled. The second is that over half of all trips in Mumbai are made on foot. Approximately 45 percent of work trips are made on foot, and the percentage is even higher for other types of trips. Because our interest from the perspective of pollution is in motorized trips, we focus on the journey to work, for which the percent of motorized trips is the highest.[10]

Table 2 indicates that, after walking (44 percent), train and public bus are the major modes used in commuting (23 percent and 16 percent, respectively). The shares of two-wheelers and cars are small (9 percent and 3 percent, respectively). If we look at higher income groups, however, the share of private

[8]The Great Mumbai Region is an area of approximately 437 sq. km. whose population in 2001 was 11.9 million. Our analysis applies to the GMR and not to the Mumbai metropolitan area, with a population of over 18 million.

[9]For multiple mode trips, the main mode is defined as the motorized mode in which the traveler spends the longest time. Walking and bicycling can be a main mode only if the trip is single mode trip.

[10]From a modeling perspective, the work trip has well a defined origin and destination. Most people take one round trip per day, so that there is no need to model trip generation.

TABLE 3: Modal Share by Purpose of Trip

	Work	Shopping	School	Social visit	Entertainment	Health Care	Personal business	Avg., all trips
On foot	45.1	82.2	55.5	52.4	51.6	66.9	47.9	52.5
Bicycle	3.5	0.4	0.4	0.4	0.0	0.8	1.2	2.2
Train	20.9	1.5	15.3	13.8	3.5	1.2	13.2	15.4
Public bus	15.1	6.2	22.3	13.1	16	12.8	18.3	14.6
Auto-rickshaw	2.1	5.4	3.3	7.6	7.0	13.2	6.7	4.3
Taxi	0.3	1.4	0.1	6.3	3.5	3.1	0.8	1.1
Two-wheeler	8.6	2.5	2.3	3.1	8.0	1.2	8.3	6.4
Own car	3.2	0.4	0.3	1.6	4.3	0.4	3.3	2.4
Other's car	0.4	0.2	0.1	1.5	6.2	0.4	0.4	0.6
Other	0.8	0.0	0.3	0.3	0.0	0.0	0.0	0.5
Total	100	100	100	100	100	100	100	100
% of total trips	47.6	15.5	9.4	8.6	4.9	3.3	10.4	100

vehicles is considerably larger (21 percent for two-wheelers and 24 percent for cars for household earning more than 20,000 rupees per month). This suggests that, as incomes increase, the demand for private vehicle use would potentially impose a burden on an already crowded city, both in terms of air quality and congestion.

The Commute Mode Choice Model

Holding residential and employment locations fixed, a traveler must decide what mode to use for the journey to work. The mode choice decision can be modeled as a discrete choice problem. Formally, let V_m denote the observable portion of the utility that is received from taking mode m and e_m the portion of utility known to the traveler but unobserved by the researcher. Typically, V_m depends on the time cost of traveling, which is broken into in-vehicle time and out-of-vehicle time (vector t_m); on the money cost of traveling (c_m);[11] and on a mode-specific constant that captures the utility of the mode common to all persons (d_m),

$$V_m = \beta_{dm} d_m + \beta_t' t_m + \beta_c g(c_m). \tag{4}$$

In model 1, $g(c_m) = c_m / \textit{hourly wage}$ so that V_m is the generalized time cost of traveling by mode m. In model 2 $g(\cdot)$ is the logarithm of daily income minus c_m, i.e., the logarithm of the Hicksian bundle. Assuming that the $\{e_m\}$ are independently and identically Gumbel distributed, the probability that mode m is chosen is given by the multinomial logit formula

$$P_m = P(V_m + e_m > V_n + e_n,\ \forall n \neq m) = \left[\exp(V_m) \Big/ \sum_n \exp(V_n)\right]. \tag{5}$$

[11] c_m is the daily round-trip cost of commuting.

In view of the well known limitations of the multinomial logit model, we also estimate a mixed logit model that allow β_{dm}, β_t, and β_c to vary across travelers according to the distribution $F(\boldsymbol{\beta}|\boldsymbol{\theta})$, $\boldsymbol{\beta} = \{\beta_{dm}, \beta_t, \beta_c)$ and θ is parameter that defines the density function. In the mixed logit model the choice probability of mode m becomes

$$(6) \qquad P_m = \int \left[\exp(V_m(\beta))/\sum_n \exp(V_n(\beta)\right] dF(\beta).$$

We assume that β_{dm} normally distributed and that β_t and β_c are lognormally distributed and estimate the mixed logit model by hierarchical Bayesian methods.

In estimating the commute mode choice models the worker is assumed to choose a commute mode from the following five options: (1) walking; (2) rail; (3) bus; (4) bus + rail; (5) motorized two-wheeler (MTW); (6) car. Bicycle, auto rickshaw, taxi, and shared ride are eliminated due to the very low frequency with which they are observed in the data. The bus + rail option assumes bus access to nearest rail station, followed by travel by rail for the rest of the trip, since most of multi-mode trips are in this form.

The choice set for each traveler is determined by the following rules: (1) The choice set for a given worker excludes two-wheeler and/or car if the household does not own one; (2) Rail and bus + rail are not an option if the nearest rail station to home and the nearest station to work are the same; (3) The walking and bus modes enter all commuters' choice sets.

A Joint Model of Vehicle Ownership and Commute Mode Choice

In the medium term, households may choose to purchase a vehicle and thus change their choice set. We model this process using a nested logit model. At the upper level of the nest the household has four choices of ownership status: (1) own neither a two-wheeler nor a car; (2) own a two-wheeler only; (3) own a car only; (4) own both a two-wheeler and a car. The systematic part of utility the household receives from mode m under nest n is

$$(7) \qquad V_{nm} = \beta_{dm}d_m + \beta_{dn}d_n + \beta_{zn}'Z + \beta_t' t_m + \beta_c^* \ln(I - O_n - c_m)$$

where d_n is a nest-specific dummy, Z is a vector of household characteristics, I is household monthly income, O_n is the ownership cost of nest n, and c_m is the cost of commuting to work by mode m. All variables in Equation (7) refer to the journey to work of the main income earner in the household. The unobserved part of utility $\{e_{nm}\}$ is distributed

$$(8) \qquad \exp\left(-\sum_{n=1}^{4}\left(\sum_{m\in S_n}\exp(-e_{nm}/\lambda_n)^{\lambda_n}\right)\right)$$

and the choice probability is

$$(9)\qquad P_{nm} = \exp(V_{nm}/\lambda_n)^* \sum_{j\in S_n} \exp(V_{nj}/\lambda_n)^{\lambda_n-1} \Big/ \sum_{k=1}^{4} \sum_{j\in S_k} \exp(V_{kj}/\lambda_k)^{\lambda_k}.$$

We could allow preference parameters to vary with household characteristics, but as our analysis suggests that it does not make much difference to the computation of elasticities, we keep fixed coefficients for simplicity.

Under each nest, the worker's choice set is generated according to the rules described in the previous section. For example, under nest (1), the commute mode choices available are walk, bus, rail and bus + rail if the worker's residential location is far enough from his work location, while nest (2) contains the choices in nest (1), plus a two-wheeler. In the model of vehicle ownership, some households simply cannot afford some of the options. We assume that if the sum of ownership cost and operating cost exceeds a household's monthly income, the option is not available to the household.

Data

The data for estimating both sets of models come from our Mumbai household survey (Baker et al., 2005). For the mode choice models, journey-to-work data come from the descriptions of the usual commute trips of the two main income earners in the household questionnaire. We asked each respondent to identify the two main income earners in the household and to describe their job locations (in terms of section and pin code),[12] earnings, and a typical journey to work (modes taken, out-of-vehicle time, in-vehicle time, out-of-pocket cost). Information was reported for 6,666 income earners from 4,979 households. In estimating commute mode choice models the following workers were dropped from the sample: (1) workers with no fixed job location (3.1 percent); (2) persons who work at home (5.6 percent); (3) workers whose workplace location was not adequately described (this includes all persons commuting to a job outside of the GMR) (4.6 percent); (4) commuters who chose bicycle, auto-rickshaw, taxi, or shared ride as their as their main mode (due to the low frequency of such choices) (5.4 percent); (5) a small number of workers who claim they commute by two-wheeler or car but do not own such a vehicle (0.3 percent). Excluding these persons resulted in 4,958 commuters.[13] Assumptions made in computing the cost, in-vehicle and out-of-vehicle travel times for modes not chosen are described in the Appendix.

[12]Mumbai is divided into 88 sections. A commuter's workplace location was considered to be the centroid of the intersection of the section and pin code (analogous to zip code) in which he worked. The geographic coordinates of residential locations were recorded for all households in the survey.

[13]Approximately 24 percent of commuters were dropped. The percent of commuters dropped is approximately the same for all income and education categories; however, commuters with vehicles were less likely to be dropped than those without.

The joint model is estimated using the data for the principal earner in each household. Most households who own a vehicle have only one car or two-wheeler, and it is usually the primary income earner who uses them for commuting. All other sampling details are the same as the commute mode choice models, resulting in a sample of 3,786 households.

Estimation Results

Table 4 presents the results of estimating the multinomial logit and mixed logit models and Table 5 the resulting elasticities.[14] Several results are worthy of comment.

The value of travel time, both in-vehicle and walking, is greater than the wage. In model 1, the value of out-of-vehicle travel time (walking time) is 1.2 times the wage; the value of in-vehicle travel time is equal to the wage. This is a common result in mode choice studies in developing countries (Deaton et al., 1987). The high value of walking time is in part a result of the high cost of bus fares in Mumbai. All travelers in our choice set face the option of walking or taking the bus. For persons for whom these are the only options and who are indifferent between walking and taking the bus, the value of time will equal the cost of taking the bus, divided by the resulting time saving.

Both the value of the income elasticities and own- and cross-price elasticities are extremely similar across models.[15] Own-price elasticities are highest for bus (−0.35 to −0.45) and car (−0.35 to −0.38) and lowest for rail (−0.07 to −0.08). It should be noted that the cost per kilometer of traveling by rail is much cheaper than the cost of bus service, especially if a monthly pass is purchased. For example, a worker with a one-way commute of 20 km pays only Rs. 90 per month to commute by rail—less than Rs. 4 per day. The cost per day of commuting 20 km via bus is, by contrast, Rs. 20. Cross-price elasticities are generally lower than own-price elasticities: for example, the elasticity of the rail modal share with respect to an increase in the bus fare is approximately 0.25.

Table 6 presents estimation results for the nested logit model of vehicle ownership and commute mode choice and Table 7 the resulting elasticities. The nested logit model includes household characteristics—the number of workers in the household (# WORKERS), whether there is a child 10 or younger in the household (CHILD), whether the household lives in the suburbs (SUBURB), the years of education of the household head (EDUCATION), and whether the head of household is self-employed—as well as time and money costs.

The results of estimating the joint model of vehicle ownership and commute mode choice are generally reasonable. The income elasticity of motor

[14]Price and income elasticities are calculated as simulated arc elasticities corresponding to a 50 percent increase in rail fare, bus fare, gas price, and income, respectively.

[15]This was, to us, somewhat surprising. One motive for estimating mixed logit models is that they admit of a richer set of substitution possibilities than the multinomial logit model (Train, 2003).

TABLE 4: Multinomial Logit and Mixed Logit Models

	Multinomial logit cost/wage		Multinomial logit ln (Hicksian bundle)		Mixed logit ln (Hicksian bundle)		
	Coef	T-value	Coef	T-value	Implied Coef.	Parameter	T-value
Const:rail (mean)	−1.829	−27.0	−1.831	−27.1		−2.906	−42.9
Const:rail (band/variance)						0.263	3.4
Const:bus (mean)	−1.803	−23.0	−1.874	−24.1		−5.050	−22.6
Const:bus (band/variance)						15.058	8.1
Const:rail + bus (mean)	−2.866	−32.0	−2.925	−32.9		−4.517	−98.6
Const:rail + bus (band/variance)						0.195	3.5
Const:two-wheeler (mean)	−0.475	−4.8	−0.532	−5.4		−1.262	−7.5
Const:two-wheeler (band/variance)						7.100	2.0
Const:car (mean)	0.023	0.2	−0.070	−0.5		−0.848	−7.3
Const:car (band/variance)						0.695	2.8
Cost/Hicsian bundle (mean)	−0.033	−15.7	13.340	14.3	25.071	3.222	54.2
Cost/Hicsian bundle (band/variance)						0.255	7.2
Walk (mean)	−0.040	−32.4	−0.039	−32.3	−0.076	−2.580	−77.0
Walk (band/variance)						0.106	5.3
In vehicle (mean)	−0.033	−13.4	−0.034	−13.6	−0.043	−3.152	−73.8
In vehicle (band/variance)						0.260	2.3
Log likelihood	−3413		−3429		−3312		
Sample size	4958		4958		4958		
Value of time (Rs./hour at mean)							
Walking	34.9		39.7		40.7		
In vehicle	29.2		33.9		23.0		

TABLE 5: Own-Price and Cross-Price Elasticties from Table 4

		Increase in			
		Rail fare	Bus fare	Gas price	Income
Multinomial logit cost/wage	Walk	0.01	0.08	0.02	−0.08
	Rail	−0.08	0.26	0.05	−0.18
	Bus	0.06	−0.45	0.06	0.28
	Rail + bus	−0.07	−0.19	0.06	0.11
	Two-wheeler	0.01	0.04	−0.22	0.11
	Car	0.01	0.03	−0.36	0.26
Multinomial logit ln (Hicksian bundle)	Walk	0.01	0.08	0.02	−0.07
	Rail	−0.07	0.25	0.05	−0.17
	Bus	0.05	−0.42	0.06	0.25
	Rail + bus	−0.07	−0.17	0.06	0.08
	Two-wheeler	0.01	0.04	−0.21	0.11
	Car	0.00	0.03	−0.35	0.25
Mixed logit ln (Hicksian bundle)	Walk	0.01	0.06	0.02	−0.07
	Rail	−0.07	0.25	0.05	−0.18
	Bus	0.04	−0.35	0.05	0.21
	Rail + bus	−0.07	−0.26	0.06	0.18
	Two-wheeler	0.01	0.03	−0.18	0.10
	Car	0.01	0.03	−0.38	0.30

vehicle ownership is 1.63 for a car and 0.47 for a two-wheeler. These figures are higher than one would find in high-income countries, but broadly consistent with findings in developing countries (Kopits and Cropper, 2005), although the latter are usually based on country-level panel data. Households with self-employed or more educated household heads are more likely to own a car or two-wheeler. Other results are more puzzling—living in the suburbs, which implies a longer commute, ceteris paribus, is not associated with higher odds of vehicle ownership—nor is having more workers in the household. The own and cross-price elasticities for mode choice are slightly lower than in Tables 4 and 5 for bus and slightly higher for car and two-wheeler.

5. IMPLICATIONS OF OUR ESTIMATES FOR POLLUTION CONTROL POLICIES IN MUMBAI

What do the estimates in the preceding section imply about the impact of various policies to control pollution from passenger transport? Of the policies we consider, the most effective policy to reduce emissions from passenger vehicles—in terms of the total tons of PM10 reduced—is to convert diesel buses to CNG. Using emissions factors from NEERI (2004) the reduction in PM10 per kilometer from converting a diesel bus to CNG would be 2.76 g/km. Applying

TABLE 6: Nested Logit Model of Vehicle Ownership and Mode Choice

Variables	Coefs	T-value
Constant:rail	−1.01	−11.47
Constant:bus	−1.09	−10.45
Constant:rail + bus	−1.73	−11.54
Constant:two-wheeler	−0.14	−1.62
Constant:car	−0.21	−2.09
Constant:own two-wheeler	−3.23	−10.50
Constant:own car	−3.78	−5.05
Constant:own both	−5.13	−5.29
Walking time	−0.02	−11.93
In-vehicle time	−0.02	−8.90
#Workers*own two-wheeler	−0.09	−1.29
#Workers*own car	−0.25	−1.88
#Workers*own both	−0.26	−1.47
Child*own two-wheeler	0.27	2.50
Child*own car	0.05	0.23
Child*own both	0.17	0.60
Suburb*own two-wheeler	−0.61	−5.49
Suburb*own car	−0.62	−2.78
Suburb*own both	−0.70	−2.01
Years of edu*own two-wheeler	0.14	7.37
Years of edu*own car	0.28	6.92
Years of edu*own both	0.27	5.37
Business owner*own two-wheeler	1.23	11.16
Business owner*own car	0.98	4.47
Business owner*own both	1.73	4.62
Hicksian bundle	7.63	18.34
Inclusive value:none	0.57	11.75
Inclusive value:own two-wheeler	0.65	10.40
Inclusive value:own car	0.39	9.01
Inclusive value:own both	0.69	4.17
Log likelihood	−4412	
Sample size	3724	
Value of time (Rs./hour at mean)		
Walking	64	
In vehicle	59	

this to a fleet of 3,391 diesel buses that travel approximately 240 million km/year would result in an emissions reduction of 662 tons of PM10 per year, 14 percent of total emissions from transport (ignoring emissions from taxis and three-wheelers).

By how much would fares have to rise to cover the cost of these conversions, and to what extent would this erode the emissions reductions calculated in the preceding paragraph? According to NEERI (2004), the capital cost of converting a diesel bus to CNG is Rs. 400,000, and the increase in operating and

TABLE 7: Elasticities from Model of Vehicle Ownership and Mode Choice (Table 6)

	Commute mode				Ownership			
Increase in	Walk	Rail	Bus	Rail + bus	MTW	Car	MTW	Car
Rail fare	0.01	−0.05	0.04	−0.05	0.01	0.00	0.00	0.00
Bus fare	0.06	0.15	−0.33	−0.03	0.05	0.02	0.02	0.01
Gas price	0.02	0.07	0.08	0.08	−0.26	−0.38	−0.12	−0.10
Income	0.15	−0.21	0.03	−0.12	0.50	1.80	0.47	1.63
Registration fee	0.07	0.06	0.11	0.07	−0.39	−0.90	−0.43	−0.99

maintenance costs Rs. 80,000 biennially. Assuming that the conversion lasts for 12 years, the annualized cost of the conversion, using an interest rate of 5 percent, is Rs. 58,095. This would raise the cost of a bus ride by Rs. 0.02 per km. Using an alternate set of figures provided by NEERI suggests a cost of Rs. 0.07 per km. Fares would have to rise by 5–10 percent to cover the cost of diesel conversions. The impact of this fare increase on shifts to more polluting modes is, however, small. An increase in the bus fare induces a very small increase in the use of two-wheelers and cars (elasticities of 0.05 and 0.02, respectively), which increases PM10 emissions by only 11 tons per year. The bigger shifts are to rail and walking, which emit no PM10. Hence, at least in Mumbai, the concern that raising bus fares to cover the cost of pollution control will cause a shift to private motor vehicles appears unfounded.

What impact will an increase in the price of gasoline have on PM10 emissions? Using Table 7 to compute the elasticity of PM10 emissions from transport yields an elasticity of only −0.04. A doubling of the price of gasoline would reduce emissions by only 4 percent, or approximately 198 tons of PM10 per year. This reflects two factors: the elasticity of two-wheeler and car emissions with respect to the price of gas, and the initial shares of two-wheelers and cars in total emissions from transport. According to Table 7, the elasticity of PM10 emissions with respect to the price of gas = −0.26 for two-wheelers and −0.38 for cars.[16] These estimates, however, reflect only adjustments in modal shares and not adjustments in the number of trips made or in trip length. Hence, these elasticities represent lower bounds.[17] The elasticities, however, are in the range

[16]Note that the elasticity of PM10 emissions for cars (two-wheelers) with respect to the price of gas ≡ the elasticity of VKTs with respect to the price of gas, assuming that the price of gas does not alter emissions per kilometer.

[17]A referee suggested that we increase these elasticities to allow for adjustments in number of trips and trip length. This could be done using data from studies in high-income countries (see, e.g., Johansson and Schipper, 1997); however, the fraction of VKTs attributable to work trips is much higher in Mumbai (approximately 2/3) than in the United States, where it is approximately 1/3, hence it is likely to be more difficult to adjust the number of trips made and their distance in Mumbai than in the United States.

of elasticities reported by Johansson and Schipper (1997). The reason that the elasticity of *total emissions* is so low is because two-wheelers and cars in Mumbai contribute only about 16 percent of PM10 emissions from transport. If we were to double the emissions elasticities for cars and two-wheelers, doubling the price of gas would reduce PM10 by about 400 tons per year—40 percent less than the CNG bus program.

A more effective strategy to control vehicle emissions would be to impose large fees on private vehicle ownership. The income elasticities in Table 7 imply that a 50 percent increase in household incomes will increase the proportion of households owning two-wheelers from 16.6 percent to 20.5 percent and the proportion of households owning cars from 5.7 percent to 10.4 percent. Imposing a tax on vehicle ownership equal to 50 percent of the purchase price (a "Singaporean" tax) implies that ownership of two-wheelers would increase to only 17.3 percent of households, while car ownership would increase to only 6.0 percent of households. The elasticity of emissions from transport with respect to a tax on vehicle ownership is −0.10, over twice the size (in absolute value) of the elasticity of emissions with respect to the price of gasoline.

Without information about the cost of air pollution control equipment for cars and two-wheelers, we are unable to calculate the optimal gasoline tax for Mumbai. We can, however, provide a rough estimate of the net benefits of a program to convert BEST buses to CNG. As indicated above, the net reduction in PM10 emissions from such a program would be on the order of 650 tons per year. To estimate the health benefits of such a reduction we rely on air quality modeling performed as part of the Urban Air Quality Management Strategy for Mumbai (World Bank, 1997) conducted in the mid 1990s. The impact of a 650-ton reduction in PM10 on mortality, conservatively calculated, is to reduce deaths in Mumbai by about 100 per year. This is based on daily time series studies relating PM10 to mortality that assume a 10 $\mu g/m^3$ reduction in PM10 will reduce daily deaths by about 1 percent. This is an extremely conservative estimate of the health benefits of reducing PM10, as it ignores the long-term impacts of particulate exposure on mortality, as well as the impacts of PM reductions on morbidity.

A rough calculation of the cost per life saved, based on the above estimate, suggests a cost of Rs. 197,000 (= 58,095*3,391/100), or approximately $4,600 USD. This is much lower than estimates of the values of a statistical life for India (Simon et al., 1999; Shanmugam, 1997), which range from 6 to 15 million rupees. Indeed, our upper bound estimate of the cost per life saved is less than the estimate of foregone earnings in Mumbai (Rs. 250,000) estimated by URBAIR (World Bank, 1997). This suggests that converting diesel buses to CNG indeed passes the benefit–cost test.

6. CONCLUSIONS

This paper examined the impacts of measures to reduce emissions from buses, cars, and two-wheelers in Mumbai, India. We have considered three possible policies: conversion of diesel buses to CNG, an increase in the price of gasoline and a tax on vehicle ownership.

Our results suggest that the most effective policy to reduce emissions from passenger vehicles—in terms of the total number of tons of PM10 reduced—is to convert diesel buses to CNG. The conversion of 3,391 diesel buses to CNG would result in an emissions reduction of 663 tons of PM10 per year, 14 percent of total emissions from transport. Indeed, the bus conversion program passes the cost–benefit test.

In contrast, our results suggest the elasticities of emissions from transport with respect to a gasoline tax and a tax on vehicle ownership are −0.04 and −0.10, respectively. As a consequence, it would take substantial increases in the gasoline tax or vehicle ownership tax to produce reductions in emissions similar to the bus conversion program. This is true even we double these elasticities to allow for adjustments in trip length and in the number of trips made, adjustments that our data do not allow us to capture. It should be emphasized that this finding primarily reflects the small share of two-wheelers and cars in the Mumbai vehicle fleet. Our estimate of the elasticity of PM10 emissions (VKTs) with respect to the price of gasoline are −0.38 for cars, and −0.26 for two-wheelers, estimates that agree with the international literature (Johansson and Schipper, 1997). The low elasticity of total vehicle emissions with respect to the price of gas reflects the fact that cars and two-wheelers account for only 16 percent of PM10 emissions from transport in Mumbai.

Would our results generalize to other Indian cities? It seems plausible that the cost per ton of PM10 reduced should be approximately the same in other large Indian cities as in Mumbai, assuming that emissions per km and VKTs per bus are roughly the same in both places. The benefits per ton of PM10 reduced will depend on the impact of reducing a ton of emissions from buses on ambient air quality and will vary directly with city population, since clean air is a public good. Thus, drawing conclusions about whether converting buses to CNG passes the benefit-cost test requires further analysis.

In terms of total PM10 reduced, the effectiveness of a gas tax vs. a program to convert buses to CNG could be different in other Indian cities. In Delhi, for example, it has been estimated that two-wheelers contribute half of the PM10 produced by transport (Society of Indian Automobile Manufacturers, 2004). Assuming that the elasticity of VKTs with respect to the price of gas is roughly the same in the two cities, the gas tax would have a larger impact on PM10 in Delhi than in Mumbai.

REFERENCES

Baker, Judy, Rakhi Basu, Maureen Cropper, Somik Lall, and Akie Takeuchi. 2005. "Urban Poverty and Transport: The Case of Mumbai," *Policy Research Working Paper* 3693, World Bank, Washington, D.C.

Burningham, Sally. 2005. Personal Communication, June 6.

Deaton, Angus, Duncan Thomas, Janet Neelin, and Bhattacharya Nikhilesh 1987. "The Demand for Personal Travel in Developing Countries." *Infrastructure and Urban Development Papers*, Report INU 1, World Bank, Washington, D.C.

Eskeland, Gunnar. 1994. "A Presumptive Pigovian Tax: Complementing Regulation to Mimic an Emissions Fee," *World Bank Economic Review*, 8(1), 373–394.

Fullerton, Don and Sarah West. 1999. "Can Taxes on Cars and on Gasoline Mimic an Unavailable Tax on Emissions?," NBER Working Paper 7059.

Glaeser, Edward L. and Matthew E. Kahn. 2003. "Sprawl and Urban Growth," NBER Working Paper 9733.

Johansson, Olof and Lee Schipper. 1997. "Measuring the Long-Run Fuel Demand for Cars," *Journal of Transport Economics and Policy*, 31(3), 277–292.

Kopits, Elizabeth and Maureen Cropper. 2005. "Traffic Fatalities and Economic Growth," *Accident Analysis and Prevention*, 37(1), 169–178.

National Environmental Engineering Research Institute. 2004. Particulate Matter Reduction Action Plan for Greater Mumbai.

Shanmugam, K. R. 1997. "Compensating Wage Differentials for Work Related Fatal and Injury Accidents," *The Indian Journal of Labor Economics*, 40(2), 112–130.

Simon, Nathalie, Maureen L. Cropper, Ann Alberini, and Seema Arora. 1999. "Valuing Mortality Reductions in India. A Study of Compensating Wage Differentials," World Bank. Policy Research Working Paper 2078.

Society of Indian Automobile Manufacturers. 2004. "Automobile Industry's Views for Control of Emissions from Mobile Sources," New Delhi. Mimeo.

Swait, Joffrey and Gunnar S. Eskeland. 1995. "Travel Mode Substitution in São Paulo. Estimates and Implications for Air Pollution Control," World Bank. Policy Research Working Paper 1437.

Train, Kenneth. 2003. *Discrete Choice Methods with Simulation*. Cambridge, Cambridge University Press.

World Bank. 1997. *Urban Air Quality Management Strategy in Asia. Greater Mumbai Report*. Jitendra J. Shah and Tanvi Nagpal (eds.) Washington, D.C.

World Bank. 2005. *For a Breath of Fresh Air: Ten Years of Progress and Challenges in Urban Air Quality Management in India*. Environment and Social Development Unit, South Asia Region.

APPENDIX. CONSTRUCTION OF VARIABLES USED IN COMMUTE MODE CHOICE MODELS

Out-of-vehicle travel time:

- Walking: Distance from home to job/0.067 (Equivalent to speed of 4 km/hour)
- Rail: Distance to nearest rail station (from home and from job)/0.067
- Bus: Answer to "How far is the nearest bus stop?" (from work and from home) from household survey. (Midpoint of the selected range is used.)
- Two-wheeler: 0
- Car: 0

In-vehicle travel time:

- Walking: 0
- Rail, Bus, two-wheeler, Car: Distance traveled/Average speed of the mode by distance category, short (1–5 km) / medium (5–10 km)/long (>10 km). [Average speed of mode calculated for each distance category using (actual in

vehicle time)/(distance to work) for persons who chose that mode. Those who traveled less than 1 km is excluded to from the estimation of travel speed because of the relatively large error involved in distance traveled.]

Money cost:

- Walking : 0
- Rail, Bus: Calculated based on the fare tables and distance traveled. The fare tables are taken from http://www.indianrail.gov.in/ (rail) and the Mumbai Metropolitan Region Development Authority (bus).
- Two-wheeler, Car: Gas price (Rs. 37.74/liter)/Gas mileage (24 km/liter for two-wheeler and 10 km/liter for car)*Distance

The distance from home to job is estimated as the distance between the worker's home (whose location is geo-reference in the survey) and his approximate work location. The work location is approximated by the centroid of the intersection of the section and pin code in which the job is located.[18] The distances to rail stations from the home and workplace have been calculated using the geo-referenced locations of train stations. The travel distance for rail is the network distance, calculated from actual rail network data.

The wage per minute is calculated as follows:

- Personal income per month/206/60 for full-time workers (assuming 8 hours per day, 6 days per week)
- Personal income per month/103/60 for non-full-time worker (assuming they work half time)

Ownership cost of vehicles:

The price of a new, entry-level compact car is Rs. 220,000 and the price of a new motorbike Rs. 32,000. One-time registration fees are Rs. 8,500 for a car and Rs. 1,500 for a motorbike. Assuming straight-line depreciation over 10 years for car and 5 years for bike, the depreciation cost is Rs. 22,850/year for a car and Rs. 6,700/year for a bike. The opportunity cost of capital is assumed to be 5 percent per year, applied to the remaining value of the vehicle each year. Averaging these costs over the usable life of the vehicle and adding comprehensive insurance costs gives us a monthly ownership cost of Rs. 3136 for a car and Rs. 834 for a motorbike.

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[18]If the pin code (section) of the work place is unavailable, the centroid of the section (pin code) is used.