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An Analysis of Various Policy Instruments to Reduce Congestion, Fuel Consumption and CO_2 Emissions in Beijing

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Abstract

Using a nested multinomial logit model of car ownership and personal travel in Beijing circa 2005, this paper compares the effectiveness of different policy instruments to reduce traffic congestion and CO_2 emissions. The study shows that a congestion toll is more efficient than a fuel tax in reducing traffic congestion, whereas a fuel tax is more effective as a policy instrument for reducing gasoline consumption and emissions. An improvement in car efficiency would also reduce congestion, fuel consumption, and CO_2 emissions significantly; however, this policy benefits only richer households that own a car. Low-income households do better under the fuel tax policy than under the efficiency improvement and congestion toll policies. The congestion toll and fuel tax require the travel cost per mile to more than triple. The responsiveness of aggregate fuel and CO_2 are, approximately, a 1 percent drop for each 10 percent rise in the money cost of a car trip.

This paper—a product of the Environment and Energy Team, Development Research Group—is part of a larger effort in the department to study climate change and clean energy issues. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at gtimilsina@worldbank.org.

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An Analysis of Various Policy Instruments to Reduce Congestion, Fuel Consumption and CO_2 Emissions in Beijing[†]

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1. Introduction

According to the International Energy Agency (IEA), the world's share of China's and India's combined CO_2 emissions grew from 9.4% in 1990 to 24.4% in 2006 (IEA, 2008). These two populous countries together accounted for 51.8% of the world's total growth of CO_2 emissions over the period. China accounted for almost as much CO_2 emissions as the United States in 2006 (5,607Mt vs. 5,697Mt), and informal reports of the acceleration of this trend suggest that China may have since surpassed the U.S. to become the world's largest emitter of greenhouse gases (GHG).

Local air pollution is the main environmental concern in China. Beijing, China's second largest city, is already one of the world's most polluted cities in terms of air quality. In Gurjar et al.'s (2008) ranking of ambient air quality in 13 of the world's megacities, Beijing places second for sulfur dioxide (SO2), second for nitrogen dioxide (NO2), and fifth for total suspended particulates (TSP). Similarly, the Millennium Cities Database (MCD, 2001) identifies Beijing as the world's most congested city as measured by average road speed. According to the World Bank (2007), the estimated cost of health damages associated with urban air pollution (i.e., from sickness and premature death) ranges from 1.2 to 3.8% of GDP, making air pollution the costliest pollution problem faced by China. The transport sector emissions in China have grown by 457% over the 1990-2006 period (IEA, 2008). The Asian Development Bank (2006) projects China's transportation energy to grow by 6% - 9% per year through 2025. Given the massive urbanization and real income growth, which result in sharp increases in private vehicle ownership, the air quality is certain to get worse.

Urbanization has potentially complex effects on the global efforts to curb GHG emissions. On the one hand, with increased urbanization and higher incomes, suburban and exurban sprawl accelerates with urban areas spreading out in low density patterns that favor mobility over longer distances by private motorized vehicles rather than by public transit or by bicycle (Ingram, 1998). On the other hand, high densities that can be achieved in urbanized areas support potential investments in rail transit systems that could greatly reduce reliance on the automobile, than if the same population were spread over more but smaller cities, each unable to support the economies of scale inherent in rail mass transit. Although it is a widely held perception that sprawl in land use causes more aggregate car miles to be driven, recent results from modern theoretical models of the urban economy in which both jobs and residences decentralize with sprawl (e.g. Anas and Rhee, 2006) suggest that the total miles driven can actually decrease with sprawl as jobs can move closer to workers during the decentralization process. Anas and Pines (2008) have shown that pricing congestion can cause population to spread from larger to smaller cities reducing total congestion, while increasing the developed land area which corresponds to more sprawl. Thus, more geographic sprawl can improve economic efficiency by reducing the total congestion externality.

Emissions and fuel use are curbed significantly not only by reducing in the distances traveled and the number of trips made, but also by improving the speed of travel, which in turn is determined by the amount of road capacity available relative to the demand. Thus any policies which can improve the speed of travel in large and highly congested cities could be very beneficial in reducing fuel use and emissions, while raising tax revenues that can be used in a variety of complimentary ways such as adding mass transit capacity or subsidizing high density developments near mass transit lines. Beevers and Carslaw (2005) have confirmed by means of simulation tests, that the congestion charging scheme implemented in central London in 2003 has resulted in significant speed improvements of about 2.1 km/hour.[1]

Beijing is a densely developed, highly congested and polluted megacity. There are a number of reasons for this. Foremost is the rapid increase in the rate of car ownership driven by the rapid per capita income growth and the limited growth in road capacity. In addition, gasoline is heavily subsidized. Together with un-priced congestion this has lowered the private average cost of travel, causing excessive use of cars in a high density built environment with average speeds in the vicinity of 18 km/hr in 2005.

Recent policies implemented in Beijing do not include aggressive pricing of traffic externalities. Instead, the authorities have extended an Olympics-related driving ban on 20% of cars each week day. Rotating this ban over the five weekdays, the policy aims to reduce congestion and pollution by rationing driving[2] (Associated Press, April 6, 2009).

We developed an aggregated model of complete travel and housing, representing Beijing circa 2005. Using the model, we compare a congestion toll and a fuel tax in terms of their impacts on consumer welfare, housing rents, car ownership and use, the number of trips, aggregate vehicle kilometers traveled, aggregate fuel consumed and aggregate emissions of CO_2.

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[1] Ultimately, reductions are also driven by fuel technology, and driving simulations of electric cars and hybrids show reductions in CO_2 emissions as documented by Saitoh et al (2005).

[2] Our model can be modified to test the effects of this policy. We propose to do this in another study.

We find that a congestion toll and a gasoline tax, both generating equal revenue, impose a very similar incremental cost per car trip and work in the desired direction qualitatively. However, they have significantly different effects quantitatively because they work on different margins of consumer behavior. The fuel tax is more effective as a policy instrument for reducing gasoline consumption and emissions because it works directly on the demand for gasoline by raising its after-tax price significantly. The congestion toll works on excess travel delay which is the source of the negative externality of traffic congestion. We also show that a policy to improve the fuel efficiency standard of cars is more efficient than a fuel tax or a congestion toll to reduce the same amount of CO_2 emissions in Beijing.

The paper is organized as follows: In section 2 the model is laid out in all its technical details. Subsection 2.1 presents the consumer preferences and the three-stage utility maximization problem. Subsection 2.2 presents the demands for travel and housing derived from the utility maximization. Subsection 2.3 discusses how the cost components of travel enter the model. These include the delay due to traffic congestion, the monetary cost of gasoline, and how the speed affected by the congestion delay determines fuel consumption and emissions. Subsection 2.4 presents the market equilibrium formulation in which the market for traffic demand and the market for housing are jointly equilibrated by solving for rents and congested equilibrium travel times. Section 3 explains how the model was calibrated from the aggregate 2005 data for Beijing, focusing especially on the calibration of the two key parameters of the congestion function, choices of which affect the results. In section 4, simulations of the effects of the congestion toll and the gasoline tax are presented and the results are compared. The same section also presents the results of two other policies (a fuel tax, and an improvement in vehicle fuel efficiency) that match the emission reductions achieved under the congestion toll. Section 5 offers some conjectures as to how the results might be modified in a setting in which more geographic detail could be included.

2. Setting up the model

Our model is derived from a consistent microeconomic formulation of the consumer's utility maximizing behavior in which discretionary trips made are choice variables because they are complementary to consumption goods that are the direct objects of choice, while nondiscretionary commuting trips are complementary to the generation of income through work. Discretionary travel is modeled as *derived demand*, determined by the consumer's disposable income, and by the full opportunity cost of a trip which is the monetary cost of the trip plus the value of the time it takes to make the trip. This approach contrasts with formulations in which the consumer is treated as if the miles themselves are the objects of consumption (see, for example, Parry and Timilsina, 2008). Our formulation allows a consumer to respond to an increase in a trip's cost by making more trips to closer destinations and fewer trips to more remote ones. This substitution of destinations of different proximities (see Anas and Rhee (2006)), is not captured in the current application because the highly aggregated nature of the Beijing data we are using does not distinguish among spatially different destinations. Still, the microeconomic structure of our model allows capturing a rich list of substitution responses by the consumers facing the toll or tax. More precisely, there are five margins that are active in the model:

(1) Switching one's commute from the car to public transit or to the non-motorized modes of bicycling and walking;

(2) Similarly switching the mode of one's discretionary (i.e. shopping) trips away from the car;

(3) Reducing the number of discretionary trips by all modes, since the toll or the tax reduces the disposable income and increases the cost of travel per trip;

(4) Giving up one's car to save the cost of operating a car, and also the annualized cost of car ownership;

(5) Renting more housing if the substitution effect of the toll or tax (which raises the delivered cost of non-housing goods) dominates over the income effect.

The fifth marginal effect is reinforced by the general equilibrium pecuniary effect that the increase in travel cost per trip caused by the congestion toll or the tax on gasoline reduces disposable income and thus housing demand. Given a fixed housing stock and fixed population in the short run, the lowered demand lowers the rent per square meter of housing. This rent reduction causes more substitution in favor of housing, compounding what was already caused by the substitution effect of the gas tax or the congestion toll. Under both taxes, the drop in the rent on housing causes welfare gains for the two lowest income quintiles. The reason for this is that relatively few poor consumers travel by car to begin with. Hence, they get little grief from the increase in after-tax monetary travel costs but benefit from the pecuniary externality of the cheaper rents. That is, for these poorest groups, the substitution effect of the tax on travel does dominate over the income effect (see effect (5) above) and this is reinforced by the lessened competition in the housing market which causes lower rents.

Our model borrows features from Anas and Rhee (2006) and its antecedents introduced into urban economics by the first author. This type of model combines the random utility theory of discrete choice contributed and refined by McFadden (1973) and widely utilized in transportation economics since then, with the constant elasticity of substitution utility function for treating a taste for variety in consumption, contributed by Dixit and Stiglitz (1977). In the present context, random utility modeling (and more precisely the nested multinomial logit model) allows us to treat discrete choices such as owning a car or not, and mode by which to commute to work daily. The Dixit-Stiglitz C.E.S. allows us to treat discretionary trip making by a variety of modes, through which goods and services are purchased by the consumer, and the trading off between discretionary trip making and housing consumption.

2.1 Consumer preferences and utility maximization

There are five types of consumers by income quintile denoted by the superscript f. The choices of consumers combine qualitative (discrete) as well as quantitative (continuous) variables in a three-level decision tree as shown in Figure 1. In the top two levels, discrete choices are made and in the bottom level the values of the continuous variables are chosen. At the first (highest) level of the tree (Figure 1), the discrete choice is whether to own a car or not, denoted by C=1, C=0 respectively. Car ownership entails an annualized acquisition cost and thus reduces the disposable income left for the lower level choices. However, car ownership also imparts satisfaction (which will be measured by idiosyncratic terms in the utility function) and enables faster travel which frees time that can be used to generate additional income. Fuel efficiency of one’s car is also key in the model because together with the travel speed, it determines the fuel cost of traveling by car. At the second level of the tree (Figure 1), the consumer chooses one of the modes for his commute to work, conditional on owning or not owning a car, determined at the first level.

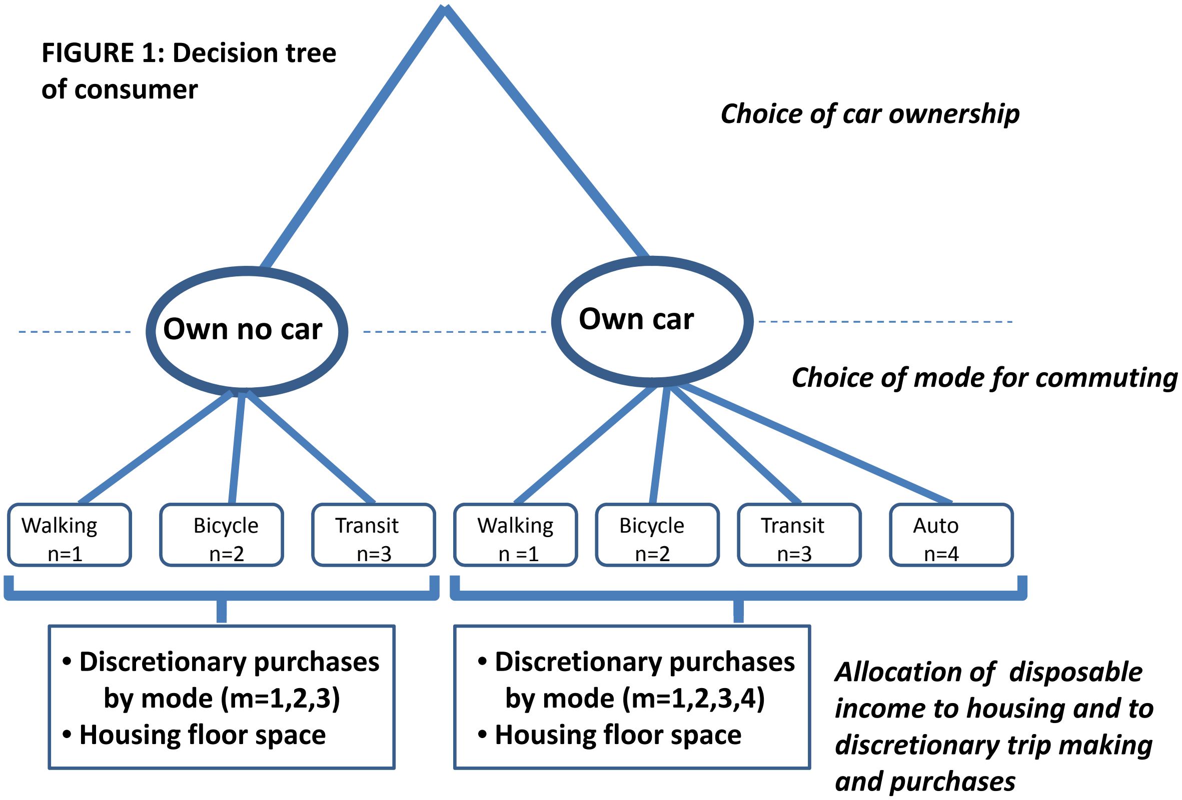

FIGURE 1: Decision tree of consumer

The commuting modes available to the consumer are walking, bicycling, public bus and transit (with the latter two assumed to be perfect substitutes) and car (denoted by n =1, 2, 3, 4). The car mode is available only to car owners. If one does not own a car, then all trips, commutes as well as non-work trips, must be made by non-car modes. Note that the model allows a consumer to own a car but not use it to commute to work. Such a car will be used together with all the other modes in non-work trip making. At the third level of the tree (Figure 1), consumers allocate their disposable income that remains after their annualized car acquisition costs and after their commuting costs determined by the choices in the first and the second levels. The disposable income is allocated between the quantity of housing to rent and the quantity of the composite good that can be purchased by making discretionary trips to "shopping" destinations utilizing some trips by each of the available modes (again cars are only available to car owners). In the case of the composite good, the consumer takes into account the numeraire price of the good per unit plus the cost of making the required number of trips to buy one unit of the good by a particular mode of travel. This cost, the unit delivered price of the good, is the sum of the monetary cost of the travel plus the value of the consumer's time used in that travel, namely the full opportunity cost of the travel.

The following nested C.E.S. utility function (1) and budget constraint (2) allow us to model the consumer's choices as described above:

$$U_{nC}^{f} = \frac{\eta^{f}}{\eta^{f}-1}\ln\left(\left[\underbrace{\left(\sum_{m=1}^{Max(3,4C)}\left(x_{mnC}^{f}\right)^{\frac{\sigma^{f}-1}{\sigma^{f}}}\right)^{\frac{\sigma^{f}}{\sigma^{f}-1}}}_{\equiv X_{nC}^{f}}\right]^{\frac{\eta^{f}-1}{\eta^{f}}} + \beta_{C}^{f}\left(h_{nC}^{f}\right)^{\frac{\eta^{f}-1}{\eta^{f}}}\right) + \nu_{nC}^{f} + \nu_{C}^{f} \qquad (1)$$

$$\sum_{m=1}^{Max(3,4C)}\left(q + g_{m}^{f} z_{m}\right) x_{mnC}^{f} + Rh_{nC}^{f} + Dg_{n}^{f} + OC = w^{f}\left(H - DG_{n} - \sum_{m=1}^{Max(3,4C)} G_{m} z_{m} x_{mnC}^{f}\right) + W^{f}. \qquad (2)$$

n = 1, 2, 3 if *C* = 0 (a car is not owned), and *n* = 1, 2, 3, 4 if *C* = 1 (a car is owned).

In the utility function, h_{nC}^{f} is the quantity of housing (floor space) rented by a consumer, which depends on whether the consumer is a car owner or not and the mode of the consumer's commute, *n*; x_{mnC}^{f}, is the quantity of the composite good purchased on a non-work trip by travel mode *m* and depending on whether a car is owned or not and on the owner's mode of commuting, *n*. The coefficients of utility function are the following. $\beta_{C}^{f} > 0$ is the preference weight of housing, assumed to vary (for calibration purposes) by whether one owns a car or not. Quantities of the composite good purchased on trips by the available travel modes are grouped together in an inner nest with a constant elasticity of substitution σ^{f}, while this group of composite good purchases has an elasticity of substitution, η^{f}, with floor space. The form of the sub-utility defined over non-work trips is Dixit-Stiglitz (1977) which has the property of the "strong taste for variety". This property causes the consumer to want to consume positive quantities of all the goods regardless of how high the unit price might be. In our context, it causes the consumer to like to utilize all of the modes available for shopping. For example, a car owning consumer will make some purchases of the composite good by walking, some by bicycling and others by public transit because he perceives these modes of travel as imperfectly substitutable activities. Finally, ν_{nC}^{f}, ν_{C}^{f}, are idiosyncratic utility constants that vary among individual consumers with common (*n, C, f*) and (*C, f*) respectively, causing the conditional commuting mode choices and car ownership choices of these consumers to vary within the income group *f*.

In the budget constraint (2), the right side is the annual cash income of the consumer. It consists of annual unearned income, W^f (which includes formal and informal income, the latter being important in China), and earned income which is the consumer's wage rate, w^f, multiplied by the consumer's annual labor supply. Labor supply is assumed to be total hours, *H*, available per year minus time spent on commuting which is the number of work days per year, *D*, times the two way length (in hours) of a day's commute, G_n, which depends on the mode of commuting *n*, minus the total time spent on discretionary trips each year, z_m being the number of round trips required by mode *m* to purchase one unit of the composite good. To buy one unit by waking, more trips must be made, to buy one unit by bicycling fewer trips suffice and to buy one unit by public transit fewer, and by car even fewer trips are needed. Therefore the constants assumed to rank as $z_1 > z_2 > z_3 > z_4$, are the "carrying capacities" of the four modes.[3] The expenditures on the left side of the budget constraint are in four groups: (i) expenditure per discretionary trip, where q =1 is the numeraire price of the composite good, and g_m^f the monetary cost of one round trip by mode *m*; (ii) the rental cost of housing, where *R* is the annual rent of one square foot of housing and h_{nC}^f is the floor space demanded by a consumer depending on whether he owns a car or not and depending on his commuting mode; (iii) the annual monetary cost of commuting by mode *n*, Dg_n^f; and (iv) the annualized cost of car ownership, O, for those who choose to be car owners (it is multiplied by C = 0 and drops out, if a car is not owned).

The above description of the consumer's utility maximization problem can be captured by the following three-level nested optimization formulation. In the innermost and third nest, the consumer knows his disposable income after having made the decision to own a car or not and after having decided by what mode to commute to work every day. This disposable income must be allocated among the housing and composite good quantities purchased on shopping trips by each of the available modes. In the middle and second nest, the consumer chooses a mode for the

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[3] Shopping for groceries is a good example: if you walk to the grocery store you can carry back a lot less than if you drove there. Clearly, not all trips entail a carrying capacity constraint, and use of this idea can also be interpreted, in our simple model, as reflecting the convenience of the more motorized and more private modes.

commute given the prior car ownership decision, and in the outer first nest, whether to own a car or not is decided. Thus, when all decisions are made, $\left\{C;\ n;\ h_{nC}^{f}, x_{1nC}^{f}, x_{2nC}^{f}, x_{3nC}^{f}, Cx_{4nC}^{f}\right\}$ is determined, where semicolons separate the stages. The model allows that consumers may use their cars for discretionary travel only (even very occasionally) owning them mainly as status symbols, a phenomenon common in China.

Thus, the overall expected utility level of consumer type depending on car ownership is:

$$U_C^{f*} \equiv E\left[\underset{n=1,2,3,4C}{Max}\left(\underset{h_{n1}^f, x_{1n1}^f, x_{2n1}^f, x_{3n1}^f, Cx_{4n1}^f}{Max} U_{nC}^{f} \text{ subject to } (2)\right)\right]. \qquad (3)$$

The final overall expected utility level after car status is chosen is $U^{f*} \equiv Max\left(U_1^{f*}, U_0^{f*}\right)$.

2.2 Demands and discrete choice probabilities

We can rewrite the budget constraint (2), so that the right side is defined as the full annual economic disposable income after commuting and car ownership, y_{nC}^{f}, while the economic prices on the left side measure the full opportunity cost of a discretionary trip including monetary as well as time cost by that mode, defined as q_m^f. In this form, the budget constraint is,

$$\sum_{m=1}^{Max(3,4C)}\left(\underbrace{q+\left(g_m^f + w^f G_m\right)z_m}_{\equiv q_m^f}\right)x_{mnC}^{f} + R\,h_{nC}^{f} = \underbrace{w^f\left(H - DG_n\right) - Dg_n^f - OC + W^f}_{\equiv y_{nC}^{f}}. \qquad (4)$$

The utility maximization problem can be solved starting with the inner and third nest, where economic income is allocated between floor space and the composite quantity. Thus,

$$\underset{\langle h_{nC}^f, X_{nC}^f \rangle}{Max}\left(\left(X_{nC}^{f}\right)^{\frac{\eta^f-1}{\eta^f}} + \beta_C^f\left(h_{nC}^{f}\right)^{\frac{\eta^f-1}{\eta^f}}\right)^{\frac{\eta^f}{\eta^f-1}} \text{ subject to } Q_C^f X_{nC}^{f} + Rh_{nC}^{f} = y_{nC}^{f}, \qquad (5)$$

where Q_C^f is the delivered composite price index of X_{nC}^{f}, and it is given by,

$$Q_C^f = \left[\sum_{m=1}^{Max(3,4C)}\left(q_m^f\right)^{1-\sigma_f}\right]^{\frac{1}{1-\sigma_f}}. \qquad (6)$$

Thus, the Marshallian demands are:

$$X^{f}_{nC} = \frac{\left(Q^{f}_{C}\right)^{-\eta^{f}}}{\left(Q^{f}_{C}\right)^{1-\eta^{f}} + \left(\beta^{f}_{C}\right)^{\eta^{f}} \left(R\right)^{1-\eta^{f}}}\, y^{f}_{nC}, \tag{7}$$

$$h^{f}_{nC} = \frac{\left(\beta^{f}_{C}\right)^{\eta^{f}} \left(R\right)^{-\eta^{f}}}{\left(Q^{f}_{C}\right)^{1-\eta^{f}} + \left(\beta^{f}_{C}\right)^{\eta^{f}} \left(R\right)^{1-\eta^{f}}}\, y^{f}_{nC}. \tag{8}$$

In a second step, the sub-demands for the goods purchased by each mode of travel are:

$$x^{f}_{mnC} = \frac{\left(q^{f}_{m}\right)^{-\sigma^{f}}}{\sum\limits_{m'=1}^{Max(3,4C)} \left(q^{f}_{m'}\right)^{1-\sigma^{f}}}\, Q^{f}_{C} X^{f}_{nC}. \tag{9}$$ [4]

Note that, given car ownership status, the ratios of expenditure $\frac{q^{f}_{m} x^{f}_{mnC}}{R h^{f}_{nC}} = \frac{\left(q^{f}_{m}\right)^{1-\sigma^{f}}}{\left(\beta^{f}_{C}\right)^{\eta^{f}} \left(R\right)^{1-\eta^{f}}}$ or $\frac{q^{f}_{m} x^{f}_{mnC}}{q^{f}_{m'} x^{f}_{m'nC}} = \frac{\left(q^{f}_{m}\right)^{1-\sigma^{f}}}{\left(q^{f}_{m'}\right)^{1-\sigma^{f}}}$ are independent of y^{f}_{nC} and, hence, independent of the mode of commuting, *n*. Equivalently, from (7)-(9), the expenditure on each good rises linearly with y^{f}_{nC}, i.e. is a constant fraction of disposable income keeping composite prices and rents constant.

Using the above derived expressions, the *conditional- on-*(*n*, *C*) *indirect sub- utility function* (i.e. maximized over $\left\{h^{f}_{nC}, x^{f}_{1nC}, x^{f}_{2nC}, x^{f}_{3nC}, C x^{f}_{4nC}\right\}$) is,

$$\hat{U}^{f*}_{nC} = \underbrace{\frac{1}{\eta^{f}-1} \ln\left[\left(\underbrace{\left[\sum_{m=1}^{Max(3,4C)} \left(q^{f}_{m}\right)^{1-\sigma_{f}}\right]^{\frac{1}{1-\sigma_{f}}}}_{\equiv Q^{f}_{C} \text{ by } (6)}\right)^{1-\eta^{f}} + \left(\beta^{f}_{C}\right)^{\eta^{f}} \left(R\right)^{1-\eta^{f}}\right]}_{\equiv \tilde{U}^{f*}_{C}} + \ln y^{f}_{nC}. \tag{10a}$$

Note that, of the two additive parts in (10a), the first part (which is determined by the rent of housing and the delivered prices of the shopped goods), is independent of the commuting mode.

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[4] By substituting equations (9) into the sub-utility expression for X^{f}_{nC}, and doing the algebra, the composite price index, (6), is derived.

The indirect utility of the consumer at the third nest, including idiosyncratic utilities, is $U_{nC}^{f} = \tilde{U}_{C}^{f*} + \ln y_{nC}^{f} + v_{nC}^{f} + \nu_{C}^{f}$. Then, the remaining discrete choice problem of the upper two nests is,

$$\underset{C=0,1}{Max}\left(\underset{n=1,..,Max(3,4C)}{Max}\left(\underbrace{\tilde{U}_{C}^{f*} + \ln y_{nC}^{f}}_{\equiv \hat{U}_{nC}^{f*}} + v_{nC}^{f} \right) + \nu_{C}^{f} \right), \tag{10b}$$

or,

$$\underset{C=0,1}{Max}\left(\tilde{U}_{C}^{f*} + \left[\underset{n=1,..,Max(3,4C)}{Max}\left(\ln y_{nC}^{f} + v_{nC}^{f} \right) \right] + \nu_{C}^{f} \right). \tag{10c}$$

By assuming that the idiosyncratic utilities, v_{nC}^{f}, are i.i.d. among the consumers according to the extreme value distribution (McFadden, 1973), the well known multinomial logit (MNL) model of discrete choice is derived, and in our case, the *commuting mode choice probabilities conditional on car ownership* take the form:[5]

$$P_{n|C}^{f} \equiv Prob\left(\ln y_{nC}^{f} + v_{nC}^{f} > \underset{\forall n' \neq n}{Max}\left(\ln y_{n'C}^{f} + v_{n'C}^{f} \right) \right) = \frac{\exp\left(\lambda^{f} \ln y_{nC}^{f} \right)}{\sum_{n'=1}^{Max(3,4C)} \exp\left(\lambda^{f} \ln y_{n'C}^{f} \right)}, \tag{11}$$

where $\sum_{n=1}^{Max(3,4C)} P_{n|C}^{f} = 1$. The coefficient $\lambda^{f} \in (0, +\infty)$ is proportional to the inverse of the variance of the idiosyncratic utilities v_{nC}^{f} in the category of consumers (*C, f*). Thus, λ^{f} is crucial in modeling taste dispersion (i.e. horizontal idiosyncratic preference variation for commuting mode within each group (*f, C*)). A value of λ^{f} close to zero indicates no sensitivity to commute-dependent disposable and extreme sensitivity to the idiosyncratic tastes only. In this case the conditional mode choice probabilities would tend to 1/3 for those who do not own a car and to ¼ for those who do. At the other extreme, as $\lambda^{f} \to +\infty$, there is no sensitivity to the idiosyncratic tastes while there is extreme sensitivity to the disposable income by mode, and that results in all consumers of that type choosing the same commuting mode.

Moving on to the utility of the choice of car status in nest 1, this utility including the expected value of the maximized indirect utility from nests 2 and 3 is $\tilde{U}_{C}^{f*} + I_{C}^{f} + \nu_{C}^{f}$ where,

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[5] The derivations are well-known and are, therefore, not discussed in detail.

$$I_C^f \equiv E\left[\underset{n'=1,\ldots,\max(3,4C)}{Max}\left(\ln y_{n'C}^f + v_{n'C}^f\right)\right] = \frac{1}{\lambda^f}\ln\sum_{n'=1}^{Max(3,4C)}\exp\left(\lambda^f \ln y_{n'C}^f\right). \tag{12}$$

Finally, the binary marginal probability of choosing car ownership status is,

$$P_1^f \equiv Prob\left(\tilde{U}_1^{f*} + I_1^f + v_1^f > \tilde{U}_0^{f*} + I_0^f + v_0^f\right) = \frac{\exp\left[\theta^f\left(\tilde{U}_1^{f*} + I_1^f\right)\right]}{\exp\left[\theta^f\left(\tilde{U}_1^{f*} + I_1^f\right)\right] + \exp\left[\theta^f\left(\tilde{U}_0^{f*} + I_0^f\right)\right]}, \tag{13}$$

where $\theta^f \in (0, +\infty)$ is the dispersion coefficient of the idiosyncratic tastes v_C^f. As was the case with λ^f, this coefficient reflects the degree of sensitivity to the idiosyncratic versus the common pecuniary aspects of car ownership.

Equations (11)-(13) together define an instance of the nested multinomial logit model. The joint probability of choosing car ownership status and mode of commuting including the utility maximizing allocation of disposable income between housing and discretionary purchases/trips is $P_{nC}^f = P_C^f \times P_{n|C}^f$.

2.3 The cost of travel

From the foregoing discussion, consumers value travel at its opportunity cost which consists of the out-of-pocket monetary cost plus the time lost in travel valued at the consumer's wage rate, since time saved in travel increases labor supply and generates more income at the wage rate. More precisely we know, based on data, that the round-trip distance required to make a trip by mode *n* is d_n on average, such that $d_1 < d_2 < d_3 < d_4$. The non-auto modes have exogenously given monetary costs per trip that do not vary by income group and are ordered such that $g_1^f = g_1 < g_2^f = g_2 < g_3^f = g_3$. In the case of auto, the monetary cost per car occupant of a round-trip depends on the cost of the fuel consumed and the number of consumers per vehicle.[6] Thus,

$$g_4^f = g_4 = \phi_4 p_F (1 + \tau_F) d_4 f(s). \tag{14}$$

In this equation, p_F is the retail price of gas per liter, τ_F is the sales tax rate on gas if any, d_4 is the round trip travel distance, and $1/\phi_4$ is the number of consumers per vehicle assumed to be a

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[6] The monetary cost of travel depends also on the car's fuel inefficiency level. However, we have formulated the model as if everyone uses a standard efficiency vehicle since we could find no data on how car fuel inefficiency varied by income in Beijing. Using the curves of fuel efficiency versus speed presented by Davis and Diegel (2004), the standard fuel efficiency is approximately that of a Geo Prizm.

constant that does not vary by income. The fuel consumed in liters per kilometer is given by the polynomial function of the traffic speed s in km/hour (see Davis and Diegel, 2004):

$$f(\hat{s}) = (3.78541178/1.6093)\times\ [0.122619 - 0.0117211\times(\hat{s}) + 0.0006413\times(\hat{s})^2$$
$$-0.000018732\times(\hat{s})^3 + 0.0000003\times(\hat{s})^4 - 0.0000000024718\times(\hat{s})^5 + 0.000000000008233\times(\hat{s})^6\ ]. \tag{15}$$

Figure 2 plots the relationship. $\hat{s} = s/1.6093$, used in (15) is the traffic speed in miles per hour used in the original equation.[7] Note that at low speeds fuel consumption per mile is very high. As speed increases fuel per km falls rapidly making a broad bottom, then rising again at high speeds. The rising portion of the curve is not relevant to our highly aggregative model, since the average speed in Beijing is very low (18.3 km/hr or 11.4 miles/hr), and falls into the rapidly falling part of the curve displayed in Figure 2.

Calculation of the speed of traffic by auto in km/hour is crucial. It is calculated as $s = d_4 G_4^{-1}$, where the congested travel time, G_4, is endogenous to the model and is determined by the road congestion function, for which we use the well-known Bureau of Public Roads form:

$$G_4 = d_4 a\left[1 + b\left(\frac{T}{Z}\right)^c\right]. \tag{16}$$

In this equation, Z is the aggregate road capacity and T is the aggregate car-equivalent volume of traffic (hereafter, "traffic") composed of cars, buses and trucks as we shall see below. The key parameters controlling congestion are b and c. We will refer to b as the "slope of congestion" and to c as the "exponential of congestion". The units of a are in hour/km and measure the reciprocal of the free-flow or uncongested speed of travel that would occur by setting $b = 0$. Given a, and the same volume to capacity ratio, TZ^{-1}, the same congested travel time can be obtained by alternative pairs of (b, c) where one parameter is increased while the other decreased. Such alternative parameter pairs would be consistent with the same travel time G_4, but give different sensitivities to congestion as reflected in the volume to capacity ratio. We will revisit this issue when we discuss how the model was calibrated.

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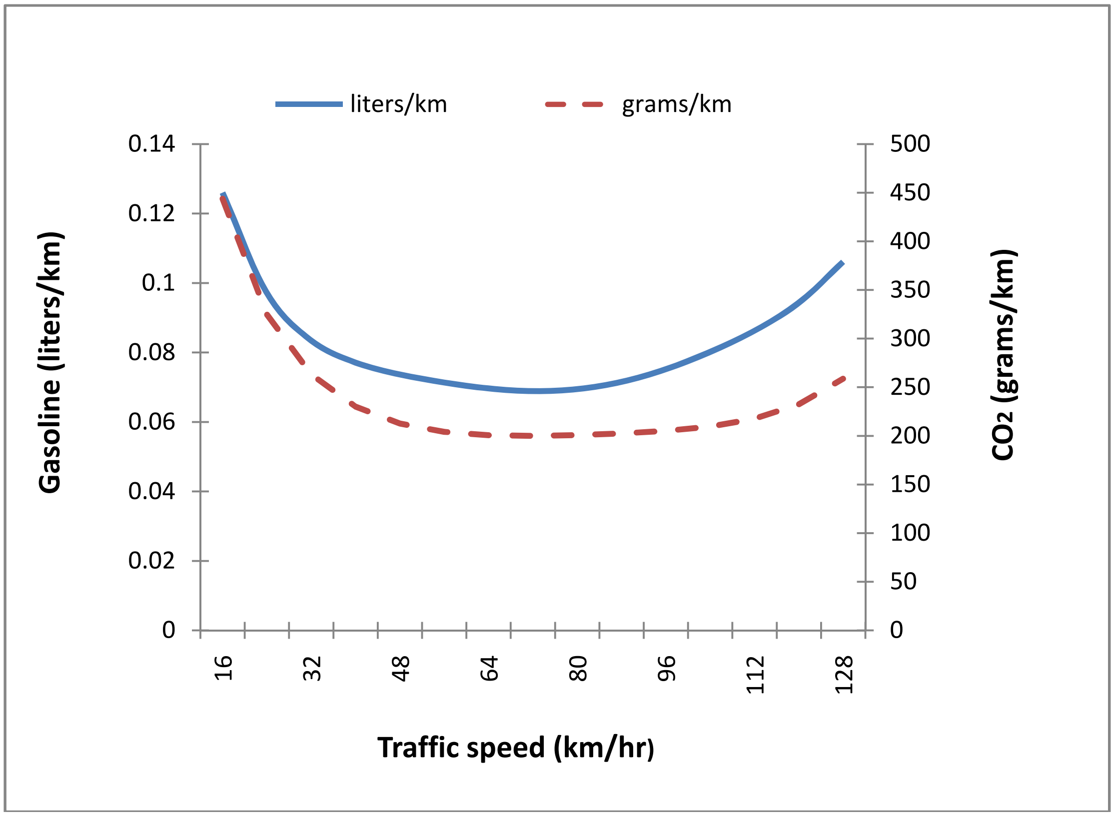
[7] The equation presented by Davis and Diegel (2004) calculates fuel use in gallons/mile from speed in miles/hour. We converted the equation to the liters/km version by making the three adjustments shown in (15). First, the speed in kilometers/ hour is divided by 1.6903 km/mile in order to get the speed in miles/hour. This is then used in the original equation to predict gas consumption in gallons/mile. Secondly, the result is multiplied by 3.785 liters/gallon to get fuel use in liters/mile and, lastly, that result is divided by 1.6903 to get the fuel use in liters/km.

FIGURE 2: Fuel consumed per car-km and grams of emissions per car-km. (Plots of equation (15) and (19))



Combining monetary and travel time opportunity costs, the privately incurred cost of one round trip by car including a toll Θ per car-trip, shared equally by the car's occupants, is

$$g_4 + w^f G_4 + \phi_4 \Theta = \underbrace{\phi_4 p_F (1+\tau_F) d_4 f \left(\left[a + ab\left(\frac{T}{Z}\right)^c \right]^{-1} \right)}_{\text{Monetary round trip fuel cost per consumer of type } f} + \underbrace{w^f d_4 a \left[1 + b\left(\frac{T}{Z}\right)^c \right]}_{\substack{\text{Value of round trip car} \\ \text{time per consumer of type } f}} + \phi_4 \Theta . \qquad (17)$$

Note that, under the assumptions we have made, the monetary cost per trip does not vary by income quintile, but the value of the travel time increases by income because the wage rate increases by income quintile. Differentiating (17) with respect to traffic volume T and knowing that more traffic means a higher congestion toll, i.e. $\frac{\partial \Theta}{\partial T} > 0$:

$$sign\left(\frac{\partial(g_4 + w^f G_4 + \phi_4\Theta)}{\partial T}\right) = sign\left\{\left(w^f - \frac{\phi_4 p_F(1+\tau_F)}{1.6903}\frac{\partial f(\bullet)}{\partial \hat{s}}\hat{s}^2\right)\frac{d_4 abcT^{c-1}}{Z^c} + \phi_4\frac{\partial\Theta}{\partial T}\right\}. \tag{18}$$

For low enough speeds so that $\frac{\partial f(\bullet)}{\partial s} < 0,$ the sign is positive indicating that more traffic increases the average private economic cost of a car trip for consumers of all income quintiles. Only at very high speeds where $\frac{\partial f(\bullet)}{\partial s} > 0,$ adding more traffic slows all traffic reducing fuel consumption sufficiently so as to possibly reduce the private average cost of a trip, provided the savings from the fuel outweigh the wage rate plus any increase in the toll. And such an effect is more likely for the low income consumers who have a low wage rate.

Finally, we will calculate CO_2 emissions in grams/km by taking the exponential of a polynomial equation that predicts log-CO_2 as a function of the speed in miles per hours (Barth and Boriboonsomsin, 2007), plotted in Figure 2 alongside the fuel consumption equation (15):

$$\begin{aligned} CO_2 &= \exp[7.613533 - 0.138655\times(\hat{s}) + 0.003915\times(\hat{s})^2 \\ &-0.00004945\times(\hat{s})^3 + 0.0000002386\times(\hat{s})^4]/1.6093 \end{aligned} \tag{19}$$

2.4 Equilibrium

The equilibrium solution of the model is found as the rent R^* at which the excess demand for housing vanishes, while the volume of car-equivalent road traffic volume, T^*, gives rise to a congested traffic speed such that the road travel time and fuel cost that arise from that speed, generate that same car-equivalent road traffic volume. We now develop the equations that express these equilibrium conditions.

The condition of short-run equilibrium in the housing market, i.e. with fixed housing floor space stock, *S*, is that excess demand for the floor space be zero:

$$\sum_{f=1}^{5} N^f\left(\underbrace{\left(1-P_1^f\right)\sum_{n=1}^{3}P_{n|0}^f h_{n0}^f}_{\substack{\text{Demand for floor space per}\\ \text{carless consumer in group } f}} + \underbrace{P_1^f\sum_{n=1}^{4}P_{n|1}^f h_{n1}^f}_{\substack{\text{Demand for floor space per}\\ \text{car-owning consumer in group } f}}\right) - S = 0, \tag{20}$$

The choice probabilities and the floor space demands per consumer are functions of (R,T) as we saw earlier. Given T , (20) can be solved for R.

Turning to the equation for the composition of traffic, it is:

$$T=(1+\phi_T A)\sum_{f=1}^{5}N^f\left(\underbrace{P_0^f\sum_{n=1,2,3}P_{n|0}^f\left(\phi_n+\frac{\phi_3 z_3 x_{3n0}^f}{D}\right)}_{\substack{\text{Car equivalent daily traffic from commuting and}\\ \text{shopping per carless consumer of type } f}}+\underbrace{P_1^f\sum_{n=1,2,3,4}P_{n|1}^f\left(\phi_n+\frac{\phi_3 z_3 x_{3n1}^f+\phi_4 z_4 x_{4n1}^f}{D}\right)}_{\substack{\text{Car equivalent daily traffic from commuting and}\\ \text{shopping generated per car owning consumer of type } f}}\right).(21)$$

In this equation, $\phi_1=\phi_2=0,$ to reflect our crude assumption that walking and bicycling do not add to traffic congestion, while $0<\phi_3<\phi_4,$ reflecting the fact that if a person trip by car contributes ϕ_4 units of traffic, then a person trip by bus contributes the lower amount, ϕ_4 . It is assumed, albeit heroically, that the total trucks are proportional to non-truck traffic through the constant A and that a truck trip contributes $\phi_T>\phi_4$ car-equivalent units of traffic. Recall that the choice probabilities and composite good demands on the right of (21) are functions of (R, T). Given R and all other variables and all parameters, (21) can be solved for a fixed-point which is the congested equilibrium traffic T^* so that $T^*=F(T^*,R),$ where $F(T,R)$ is the right side of (21) expressed as a function of the traffic T.

To find the equilibrium, (20) and (21) are solved simultaneously for (T^*,R^*) given all the parameters and exogenous variables of the model.

3. Data and calibration

Our data approximates 2005 conditions. The geographic scope of Beijing in our study is the "Beijing Metropolitan Area", which is the core area of the much larger Beijing Administrative Area.[8] In the economic sense, this core urbanized area of Beijing includes the four central-city districts and the four inner-suburb districts, defined as the Beijing Metropolitan Area, and covers

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[8] The larger administrative area includes the four central-city districts (*Dongcheng, Xicheng, Chongwen, Xuanwu*), the four inner-suburb districts (*Chaoyang, Haidian, Fengtai, Shijingshan*), the 8 remote districts (*Fangshan, Tongzhou, Shunyi, Changping, Daxing, Mentougou, Huairou, Pinggu*) and the 2 remote counties (*Miyun, Yanqing*). The 8 remote districts and the 2 remote counties are rural areas with some small satellite towns which are not fully integrated into the Beijing labor market.

1368.32 square kilometers. In 2005, there were 9.53 million permanent residents within this area, defined as those who have lived in Beijing for at least half a year, with or without a *Hukou*.[9]

The Beijing Metropolitan Area is characterized with high population density and very rapidly increasing car ownership due to rapidly rising per capita income. Between the years 2000 and 2007, the number of cars in Beijing doubled from 1.5 to 3 million. Travel demand has outstripped road capacity and, as a result, traffic flows at very low speeds in the vicinity of 18 km/hr (IAPT, 2007). As a result, congestion and pollution from vehicles are very high and the air quality quite bad. The PM10 concentration in Beijing ($141\ \mu g/m^3$ in 2005) was roughly four times higher than that in Los Angeles. The NOx concentration is also very high ($66 \mu g/m^3$ in 2005).

In calibrating the model to the data that we were able to gather, we assumed that each employed consumer works 250 days per year and that a total of 3000 hours per year is available for allocation between working and traveling. Other data that varies by mode and by income quintile is shown in Tables 1 and 2. The calibration procedure starts with the raw data observations listed in these tables. From these, the monetary cost and travel times of trips by mode and car ownership status are first calculated. Then, the wage and non-wage incomes are used to construct the disposable incomes after car ownership and commuting mode decisions, i.e. the y_{nC}^f. The elasticity of substitution σ^f among the modes used in non-work travel is set to 0.5 and so is the elasticity of substitution η^f between housing and non-housing goods. Given the shares of income spent on housing by mode of commuting (see Table 2), the housing weight coefficients β_C^f are calibrated so that these shares are replicated. Following this, the nested logit model's dispersion parameters λ^f, θ^f are calibrated so that a reasonable price and income elasticity is obtained. In calibrating λ^f we decreased its value with income to reflect the assumption that the choices of the poor are more sensitive (more elastic) in response to price and

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[9] The *Hukou* system was established in the former central-planning era. *Hukou* is determined by where one was born. The first level is urban *Hukou* versus rural *Hukou*. The second level is the location of *Hukou*, (province and city if urban *Hukou*, or village if rural *Hukou*). Prior to the 1980's, *Hukou* was a quota of people who were allowed to migrate to a city. If you held a rural *Hukou*, you could not move to a city, unless you could successfully obtain an urban *Hukou*. Similarly, you could not move from the city where your *Hukou* was located to another city if you did not obtain the *Hukou* quota in the latter city. But since the 1980's, this constraint on labor mobility has been relaxed step by step, which stimulated huge migrations from rural places to urban places, from small cities to large cities, and from the interior region to the coastal region. Currently, people do not need a *Hukou* quota to stay in a city. People do not need *Hukou* to buy houses, and they do not need *Hukou* to find jobs, either. Thus, the *Hukou* population is now much smaller than the actual population.

disposable income changes. Mode and car choice specific constants are added to the utility function and are set so that the shares for mode of commuting and car ownership that are given by the data for each quintile are replicated. Table 3 shows the variation by income quintile of the elasticities produced by the calibrated model.

TABLE 1: Basic data for the modes of travel

	Walk	**Bicycle**	**Bus**	**Car**
Average trip length (2 way kms), d_n (*)	0.8	5.57	22.4	26.0
Trip times (2 way hrs.), G_n (*)	0.43	0.70	1.86	1.4341
Speed (km/hr), v (**)	1.86	7.96	12.04	18.13
Fuel price, (RMB/liter), p_F	n/a	n/a	n/a	4.26
Car equivalent traffic load of one passenger, ϕ_n (#)	0	0	0.083	0.5714
Annualized car ownership cost (RMB/year), O	n/a	n/a	n/a	5750
Average monetary cost of trip per worker (RMB/2-way trip), g_n (**)	0	0.35	2.5	7.381

(*) As reported in Zheng, Peiser, Zhang (2009, in press).
(**) Source: The Beijing Municipal Institute of City Planning and Design (BMICPD) and the *2005 Transportation Survey* conducted by the Beijing Municipal Committee on Transportation.
(#) Sources: Interview with experts at BMICPD, the "2005 Transportation Survey" conducted by the Beijing Municipal Committee on Transportation.

From discussions with transportation planners and casual observations, it appears that a car in Beijing typically carries 1.75 people. Therefore, each person-trip by car is assumed to cause ϕ_4 =0.5714 (=1/1.75) car-equivalent traffic units. A Beijing bus is believed to cause three times the congestion as does a car, and carries about 32.5 passengers on average. Hence, the car-equivalent traffic generated by a bus ride is 0.0923 (= 3/32.5). Mode 3 is transit which includes subway and bus, and about ten percent of transit trips are reportedly by subway. Therefore, we set $\phi_3 = 0.9 \times (0.0923) = 0.083$. A typical truck in Beijing causes 1.7142 times the car-equivalent traffic load. Hence, $\phi_T = 1.7142$. One truck vehicle trip is assumed to occur for each ten car-equivalent non-truck traffic unit. Hence, *A*=0.1 in (21).

TABLE 2: Data by income quintiles

		$f = 1$	$f = 2$	$f = 3$	$f = 4$	$f = 5$
Population of workers (*)		1,050,962	1,156,764	1,156,764	1,220,245	1,156,764
Wage (RMB/hr)		6.61	8.47	10.56	12.66	23.59
Nonwage income, including formal and assumed informal nonwage income		1,044	2,832	10,560	20,451	70,770
Income share of housing in disposable economic income per worker		0.63	0.50	0.445	0.40	0.34
Aggregate floor space (**) (millions of square meters)		28.63	31.90	35.50	40.30	58.32
Car ownership rate		0.005	0.05	0.20	0.50	0.90
Cars owned		3,028	33,027	132,222	348,611	594,890
Share of car owners commuting by car		30%	6.5%	9.2%	18.4%	42%
Commute shares of carless	*Walk*	*0.17*	*0.12*	*0.12*	*0.09*	*0.18*
	Bike	*0.29*	*0.27*	*0.25*	*0.24*	*0.19*
	Bus	*0.54*	*0.61*	*0.63*	*0.67*	*0.63*
Commute shares of car owners	*Walk*	*0.17*	*0.11*	*0.11*	*0.07*	*0.10*
	Bike	*0.29*	*0.25*	*0.22*	*0.20*	*0.11*
	Bus	*0.54*	*0.58*	*0.58*	*0.54*	*0.37*
	Auto	*0.00*	*0.06*	*0.09*	*0.19*	*0.42*

(*) Source: *Beijing Statistical Yearbook.*
(**) Sources: *Beijing Statistical Yearbook* and survey conducted by the Beijing Municipal Construction Committee.

TABLE 3: Calibrated elasticity by income quintile

	$f = 1$	$f = 2$	$f = 3$	$f = 4$	$f = 5$
Income elasticity of car ownership with respect to the car acquisition price for car owners	10.06	9.57	8.03	5.01	1.00
Price elasticity of car ownership with respect to the car acquisition price for car owners	-4.69	-2.97	-1.47	-0.63	-0.05
Travel time elasticity of the demand for the choice of mode (average over modes)	-0.44	-0.23	-0.14	-0.09	-0.04
Rent elasticity of the demand for housing (floor space)	-0.82	-0.75	-0.72	-0.70	-0.67

Free flow (uncongested) traffic speed is assumed to be 80 km/hr. Thus, in the congestion function given by (16), we set a=1/80 = 0.0125. In order to calibrate the road capacity (Z) and the coefficients b and c, we proceeded as follows. We first set b = 0.24 and c = 4.0. Having done this, we calculated the value of the road capacity Z, so that given the traffic T generated by the calibrated relationships described, the round trip travel time by car G_4 agrees with the observed. The next step was to choose b and c in such a way that the sensitivity of the model to congestion (or to a congestion toll) is not too high or too low. Given the calibrated volume to capacity ratio, T / Z, if one chooses a lower c, then one must raise the value of b sufficiently so that the new coefficients still replicate G_4. Table 4 shows the pairs of b and c that we tried. We did this by changing c by 0.5 at a time while recalibrating b each time. For each pair in the table, we simulated a Pigouvian toll designed to internalize the total excess delay due to congestion (to be discussed in section 4) and then we observed how key model aggregates were affected. The table shows seven alternative pairs of b and c calibrated as explained above so that in each case, the calibrated car travel time per round trip ($G_4 = 1.4341$) occurs at equilibrium when congestion is not priced. The reaction of this calibrated equilibrium to the imposition of the Pigouvian congestion toll is different, however. Going from left to right in the table, the sensitivity to congestion increases and thus the toll increases. As the toll increases, car-equivalent traffic decreases by switches to other modes, and speed increases. Fuel consumption, emissions and vehicle kilometers of car travel all decrease, while aggregate revenues from the toll increase. Observing the results in this table, we decided that $c = 2.0$ and $b = 0.905$ were the most plausible values because they were "middle of the road". Therefore, we used this pair of values in the simulations.

TABLE 4: The sensitivity to congestion tolls under alternative calibrated congestion function parameters

Road capacity(calibrated)	Z = 1.3489						
Car round trip travel time	G_4 (hours/trip) = 1.4341						
c, Exponent of congestion function		1.0	1.5	2.0	2.5	3.0	3.5	4.0
b, Slope of congestion function		1.7574	1.2611	0.9050	0.6494	0.4661	0.3344	0.2400
	Calibration as base							
Toll for delay (RMB/km.)	0	0.80	1.09	1.31	1.47	1.59	1.68	1.75
T, Traffic ($\times10^6$)	2.62	2.31	2.24	2.20	2.18	2.17	2.17	2.17
v, Speed (km/hr)	18.13	19.96	21.61	23.42	29.21	31.00	28.97	30.75
Car kilometers/day ($\times10^7$)	4.36	3.65	3.49	3.40	3.35	3.33	3.32	3.32
Car fuel cons.(liters) ($\times10^6$)	5.09	3.99	3.63	3.37	3.17	3.02	2.91	2.83
CO_2 emissions (grams) ($\times10^{10}$)	1.77	1.38	1.24	1.13	1.05	0.99	0.94	0.90
Toll revenue (RMB/day) ($\times10^7$)	0	2.93	3.81	4.45	4.93	5.30	5.58	5.81

4. Policy simulations: congestion toll versus gasoline tax

Table 5 displays the policy simulation results. The first column in the table is the calibrated case with (c = 2.0 and b = 0.905), corresponding to the base case equilibrium circa 2005 in which there is no pricing aimed at remedying excess congestion or excess fuel consumption.

The next columns correspond to the two pricing policies on car traffic that we tested. The first policy is the Pigouvian congestion toll per km of travel levied on each car traveler, internalizing only the excess delay from congestion, and the second policy is a fuel tax per liter of gasoline. First, we imposed the Pigouvian toll on excess delay and we calculated the results shown in column two including the aggregate toll revenue raised. Then, we imposed a tax per liter of gasoline and adjusted the tax rate in such a way that the same aggregate tax revenue was raised as in the case of the congestion toll.

TABLE 5: Impacts of congestion toll and gasoline tax in Beijing while generating the same revenue

	Un-priced excess congestion (Base Case)	**Revenue neutral alternative taxes**	
		Tolls on excess delay (% changes from base)	**Gasoline tax** (% changes from base)
Aggregate floor space (sq. m.)	239,090,000	239,090,000	239,090,000
Rent (RMB/sq.m./year)	500	493.39	491.44
Traffic speed (km/hr)	18.13	23.42	25.47
Auto round trip time (hrs/trip)	1.4341	1.1103	1.0207
After-tax cost of a car trip (RMB/trip)	7.3810	26.81	33.81
Value of time of car users (RMB/hr)	20.77	21.65	21.91
Total auto person-trips per day	2,936,200	2,291,200 (-22.0%)	2,089,100 (-28.9%)
Total bus person-trips per day	6,727,900	6,896,100 (+2.5%)	6,956,400 (+3.4%)
Traffic (car equivalent units/day)	2,619,500	2,204,100 (-15.9%)	2,074,700 (-20.8%)
Cars owned	1,111,700	885,300 (-20.0%)	814,100 (-26.8%)
Auto aggregate kilometers per day	43,621,000	34,040,000 (-22.0%)	31,037,000 (-28.8%)
Car aggregate travel time (hours/day)	4,210,700	2,543,800 (-39.6%)	2,132,500 (-49.4%)
Auto aggregate fuel cons. (lit./day)	5,087,300	3,366,900 (-33.8%)	2,919,100 (-42.6%)
Auto CO_2 emissions (grams/day) ($\times 10^3$)	17,716,000	11,342,000 (-36.0%)	9,695,400 (-45.3%)
Aggregate rents (RMB/year)	119,550,000,000	117,790,000,000	117,500,000,000
Average social welfare	7.3986	7.3873	7.3837
Income quintile 1	*5.8907*	*5.8985*	*5.9009*
Income quintile 2	*6.7415*	*6.7453*	*6.7467*
Income quintile 3	*7.3495*	*7.3449*	*7.3442*
Income quintile 4	*7.8335*	*7.8095*	*7.8035*
Income quintile 5	*9.0161*	*8.9790*	*8.9647*
Fuel per km. of car travel (liters/km.)	0.1168	0.0989	0.0941
Fuel per auto round trip (liters)	3.0323	2.5717	2.4453
Congestion toll or fuel tax (RMB/km)	0.00	1.3078	1.4344
Congestion toll or fuel tax (RMB/ person for a round trip by car)	0.00	19.43	21.31
Aggregate daily tax revenue (RMB/day)	0.00	44,510,000	44,518,000

The Pigouvian congestion toll

The Pigouvian congestion toll should be computed on each kilometer as the social marginal cost minus the average private cost of adding a car to the traffic stream. This then would be the externality imposed by one car on all the traffic. A unit amount of car-equivalent traffic, T, affects the travel time per km., G_4 / d_4 via (16), by creating excess delay, but since this changes the speed, the rate of fuel consumption and emissions per km are also affected by (14) and (15). The aggregate excess delay caused by each car, is $T\left(\frac{\partial G_4}{\partial T}\right) = d_4 abc\left(\frac{T}{Z}\right)^c$. The toll paid by each car-equivalent traffic unit, fully internalizing both the excess delay and the excess fuel use would then be,

$$\begin{pmatrix} \textit{FULL TOLL} \\ \textit{PER CAR} \\ \textit{PER TRIP} \end{pmatrix} = \underbrace{\underbrace{\hat{w}}_{\substack{\textit{Avg. value} \\ \textit{of time} \\ \textit{per hour} \\ \textit{of cars} \\ \textit{on the road}}} \left(\underbrace{T\left(\frac{\partial G_4}{\partial T}\right)}_{\substack{\textit{Excess delay caused} \\ \textit{by each car (hours)}}} \right)}_{\textit{TOLL PER TRIP FOR EXCESS DELAY}} + \underbrace{\underbrace{p_F \left(-\frac{\partial f(\bullet)}{\partial \hat{s}}\right)\left(\frac{d_4 / 1.6093}{G_4^{\,2}}\right)}_{\textit{Value of fuel saved per hour}} \left(\underbrace{T\left(\frac{\partial G_4}{\partial T}\right)}_{\substack{\textit{Excess delay caused} \\ \textit{by each car (hours)}}} \right)}_{\textit{TOLL PER TRIP FOR EXCESS FUEL}} . \tag{22}$$

In (22), $\hat{w}$ is the average wage rate (or value of time) of the car travelers sharing the road capacity. The toll per kilometer per car occupant is obtained from (22), by dividing with trip distance, d_4, and multiplying by ϕ_4, the car occupancy rate. We will study a toll levied to internalize only the excess delay, ignoring the additional toll that could be levied to internalize the fuel externality.

The tax on fuel

A good initial guess of the tax rate on fuel can be calculated roughly from the toll on delay so that the fuel tax per km of travel by car is equal to the congestion toll per km. Thus suppose that the congestion toll per km paid by a car is τ_C, then set $p_F \tau_F f(\hat{v}) = \tau_C$. Solving this for the tax rate on fuel, τ_F, we get $\tau_F = \tau_C (p_F f(\hat{v}))^{-1}$. Since this fuel tax rate, $\hat{\tau}_F$, results in the same tax per km as does the toll on excess delay, and since the model consists of a single aggregated road , the two taxes would have identical effects. However, the fuel tax revenue as a function of the fuel tax rate is inverse U-shaped. Hence, there exists a higher fuel tax rate that yields the same revenue as the toll on excess delay only. Starting from this initial guess, we adjust the fuel tax rate, τ_F, upwards from $\hat{\tau}_F$ until the aggregate revenue raised from the fuel tax is the same as that raised from the congestion toll. We find this revenue neutral fuel tax rate to be $\tau_F = 3.58,$ or 358% of the pre-tax price of fuel (which is 4.26 RMB/liter).

Comparison of the two pricing schemes

From Table 5, the congestion toll is 1.31 RMB/km or 19.3 RMB/person-car-trip and the revenue neutral fuel tax is 1.43 RMB/km or 21.31 RMB/person-car-trip. Imposing such tolls raises the monetary cost of an auto trip by about 3.5 times. The reason such tolls are so high is easily explained by the fact that the monetary cost elasticity of travel by car is low and the level of road congestion delay in Beijing is very high. Because the level of congestion is so high, steep tolls are needed to internalize the excess delay. But because the demand is inelastic, the tolls must be that much higher to achieve the required reduction in the excess delay. The tax avoidance response of the consumers to the toll and the gas tax was discussed in more detail in the Introduction. The aggregate revenue raised by these equivalent taxes is 44.5 million RMB per day or about 5.5 million in U.S. dollars. The toll on delay is more efficient than is the equivalent tax on fuel. This can be verified from the social welfare in Table 5, the weighted average of the expected utility of the five quintiles, and the aggregate rents each decrease less from their base values under the Pigouvian toll than under the revenue neutral fuel tax.

Looking at the variation of the welfare change by income quintile, the lowest two income groups benefit from the imposition of the congestion toll and benefit even more from the imposition of the fuel tax, but the highest three quintiles are hurt by the imposition of the congestion toll and are hurt more by the fuel tax. As explained in the Introduction, the reason the lowest two quintiles benefit from these pricing policies is because both policies reduce the rent of housing (see Table 5). This rent reduction is sufficient to cause all consumers who do not own cars to benefit, since they are not directly impacted by the tolls or by the fuel tax. In the case of consumers who own cars, the income effects of the higher tolls or the fuel tax causes welfare to be reduced despite the drop in rents and the substitution effect of the increase in the after-tax composite delivered price of goods bought by discretionary travel. In the case of the two lowest quintiles, those who own cars are small parts of the total. Therefore, considering the entire population of consumers in these quintiles, the welfare effect is positive for these quintiles. In the highest three quintiles the car owners are more numerous and the overall effect of both tolls and the fuel tax is negative on the welfare of these quintiles.

The effect of the two taxes on all the other performance measures such as vehicle-kilometers, trips by car, car ownership, fuel consumption, and CO_2 emissions, are as expected. Each of these aggregates is reduced. The most important finding is that the fuel tax outperforms the congestion toll's impacts by as much as 25% to 50%. For example, the congestion toll increases traffic speed by 29% from 18.13 km/hr to 23.42 km/hr. The fuel tax increases the speed from 18.13 km/hr to 25.47 km/hr, or 50% more than the congestion toll increases it. Percentage changes from the base case in which congestion is not priced are shown in parentheses in columns 2 and 3 of Table 5. Emissions are reduced by about 36% when the toll is levied but by 45% (25% better than the toll) when the gas tax is used. The toll reduces fuel use by cars by 34% but the gas tax again does about 25% better by reducing it by 43%. Table 6 shows the adjustments that occurred along the various margins under the two policies.

TABLE 6: Effects of the congestion toll and the fuel tax on the margins of adjustment

Income quintile, f		*1*	*2*	*3*	*4*	*5*
Total floor space (m^2)	*Base*	87,000	1,140,000	6,839,000	23,673,000	92,104,000
	Toll	*-34%*	*-50%*	*-45%*	*-36%*	*-7.5%*
	Fuel tax	*-44%*	*-60%*	*-56%*	*-47%*	*-11.1%*
Cars owned	*Base*	3000	33,050	132,190	348,620	594,880
	Toll	*-34%*	*-46%*	*-43%*	*-34%*	*-5.7%*
	Fuel tax	*-42%*	*-60%*	*-54%*	*-44%*	*-8.6%*
Commutes by car	*Base*	10	3760	21,280	112,260	436,220
	Toll	*-100%*	*-63%*	*-51%*	*-39%*	*-7.0%*
	Fuel tax	*-100%*	*-75%*	*-63%*	*-50%*	*-10.0%*
Non-work car trips	*Base*	700	15,800	113,600	455,300	1,777,200
	Toll	*-94%*	*-58%*	*-53%*	*-45%*	*-16.0%*
	Fuel tax	*-57%*	*-68%*	*-64%*	*-56%*	*-22.0%*
Total non-work trips	*Base*	1800	39,300	284,800	1,150,500	4,651,400
	Toll	*-39%*	*-53%*	*-48%*	*-40%*	*-11.0%*
	Fuel tax	*-50%*	*-63%*	*-59%*	*-51%*	*-15.7%*

Other policies that achieve equivalent reductions in emissions

In the above we used revenue neutrality (equal revenue generation) as the basis for comparing the congestion toll and fuel tax. Since an important objective of these instruments here is to reduce CO_2 emissions, it would also be logical to compare the impacts of the policies when they are designed to reduce emissions to the same level. Table 7 lists the results of two such emissions-neutral policies. The first is a fuel tax policy and the second a mandated improvement in car fuel efficiency. These are designed so that the same aggregate reduction in CO_2 emissions is achieved as that achieved by the congestion toll. We find that to reduce the same amount of CO_2 as in the case of the toll (i.e. by 36%), the fuel tax should be set at a level of 263%, lower than the revenue equivalent level of Table 5 (358%). If a fuel efficiency improvement (km/liter) is mandated, instead of a congestion toll or a fuel tax, then the average fuel efficiency of automobiles would have to be increased by 40% (from 19.2 miles/gallon in the base case to 32.2 miles/gallon), to achieve the same reduction in carbon emissions.

It is interesting to note that the fuel efficiency improvement policy (Column 3) has slightly superior impacts on welfare impacts as compared to the congestion toll and fuel tax policies. Such an improvement economizes on fuel per km of car travel and thus reduces the fuel cost of a trip by car. This causes more cars to be owned and used, and aggregate congestion and fuel use increases as a result. Welfare is improved on average because of the fuel cost savings per trip. However, higher welfare would be enjoyed only by the consumers in the richer income quintiles (quintiles 4 and 5) who have a higher demand for cars and for driving. The rest of the consumers would do worse than in the fuel tax case.

The welfare effects of the fuel tax policy relative to the congestion toll are better for the four lowest quintiles. The richest quintile, however, does worse. While the fuel tax generates about 6.7 million less revenue daily than the congestion toll generates, the efficiency improvement policy does not generate any revenue (although it does increase rents). Lacking data on the changes in auto ownership costs that would be entailed by the changes in the legislated car efficiency levels, we could not treat this policy well enough. Anecdotally, more efficient cars in China are also cheaper to own. This would cause everyone to own only the most efficient cars, were it not for systematic and idiosyncratic preferences favoring the inefficient cars because they are safer, more comfortable and better status symbols. Since we could not capture these aspects, column 3 in Table 7 probably overestimates the benefits of the hypothetical efficiency improvement.

TABLE 7: Impacts of congestion toll, gasoline tax and vehicle efficiency improvement while reducing the same CO_2 emissions

	Tolling for excess delay only **(% changes from base)**	**Equivalent emission reductions**	
		Gasoline tax	**40% improvement in car fuel efficiency**
Aggregate floor space (sq. m.)	239,090,000	239,090,000	239,090,000
Rent (RMB/sq.m./year)	493.39	493.39	501.24
Traffic speed (km/hr)	23.42	23.41	17.36
Auto round trip time (hrs/trip)	1.1103	1.1105	1.4978
After-tax cost of a car trip (RMB/trip)	26.81	26.79	4.3991
Value of time of car users (RMB/hr)	21.65	21.65	20.61
Total auto person-trips per day	2,291,200 (-22.0%)	2,291,700	3,051,000
Total bus person-trips per day	6,896,100 (+2.5%)	6,896,000	6,700,500
Traffic (car equivalent units/day)	2,204,100 (-15.9%)	2,204,400	2,693,600
Cars owned	885,300 (-20.0%)	885,450	1,153,600
Auto aggregate kilometers per day	34,040,000 (-22.0%)	34,047,000	45,327,000
Car aggregate travel time (hours/day)	2,543,800 (-39.6%)	2,544,900	4,569,700
Auto aggregate fuel cons. (lit./day)	3,366,900 (-33.8%)	3,368,000	3,241,300
Auto CO_2 emissions (grams/day) ($\times 10^3$)	11,342,000 (-36.0%)	11,346,000	11,341,000
Aggregate rents (RMB/year)	117,790,000,000	117,970,000,000	119,840,000,000
Average social welfare	7.3873	7.3873	7.4006
Income quintile 1	*5.8985*	*5.9047*	*5.8893*
Income quintile 2	*6.7453*	*6.7554*	*6.7410*
Income quintile 3	*7.3449*	*7.3940*	*7.3509*
Income quintile 4	*7.8095*	*7.8314*	*7.8385*
Income quintile 5	*8.9790*	*8.3694*	*9.0212*
Fuel per km. of car travel (liters/km.)	0.0989	0.0989	0.0715
Fuel per auto round trip (liters)	2.5717	2.5721	1.8592
Congestion toll or fuel tax (RMB/km)	1.3078	1.1083	0
Congestion toll or fuel tax (RMB/ person for a round trip by car)	19.43	16.47	0
Aggregate daily tax revenue (RMB/day)	44,510,000	37,735,000	0

Moreover, the increase in fuel efficiency might entail huge investment higher vehicle acquisition and maintenance costs or disutility from having to own more efficient vehicles which are, on average, less comfortable and less safe. Due to data limitations, these costs of mandating a higher fuel efficiency standard are not accounted that is not accounted in the model. The welfare effects of the fuel tax policy relative to the congestion toll are better for the four lowest quintiles. The richest quintile, however, does worse. Quintiles 3 through 5 do better than under the congestion toll, while the lower quintiles suffer the higher congestion without owning many more cars, so they do worse than under the congestion toll.

Lacking data on the changes in auto ownership costs that would be entailed by the changes in the legislated car efficiency levels, we could not treat this policy well enough. Anecdotally, more efficient cars in China are also cheaper to own. This would cause everyone to own only the most efficient cars, were it not for systematic and idiosyncratic preferences favoring the inefficient cars because they are safer, more comfortable and better status symbols. Since we could not capture these aspects, column 3 in Table 7 probably overestimates the benefits of the hypothetical efficiency improvement.

5. Concluding remarks

Using a nested multinomial logit model of car ownership and personal travel in Beijing circa 2005, we compared the effectiveness of three policy instruments, a congestion toll, a gasoline tax and car efficiency improvement to reduce aggregate CO_2 emissions. The gasoline tax and congestion toll were also compared in revenue neutral fashion. The indicators used in the comparisons are consumer welfare, housing rents, car ownership and use, the number of trips, aggregate vehicle kilometers traveled, aggregate fuel consumed and aggregate emissions of CO_2.

The key findings of the study are as follows: (i) a congestion toll is more efficient than the fuel tax in reducing traffic congestion, since it works on excess travel delay which is the source of traffic congestion; (ii) a fuel tax is more effective as a policy instrument for reducing gasoline consumption and emissions because it works directly on the demand for gasoline by raising its after-tax price significantly; and (iii) an improvement of car efficiency would be more efficient than a congestion toll and a fuel tax while reducing the same amount of fuel consumption and CO_2 emissions because aggregate social welfare is higher under this policy than those in other two policies. However, this policy benefits only richer households who own car. Low income households do better under fuel the tax policy than under the efficiency improvement and the congestion toll policies. Moreover, the efficiency improvement policy does not generate any revenue and it might entail vehicle acquisition and maintenance costs and utility losses from using more efficient vehicles

As explained in the Introduction, the model treats the responses of consumers to policies along five margins: car ownership, commuting mode choice, total number of discretionary trips, share of discretionary trips by car and the allocation of disposable income between goods shopped by making discretionary trips and housing. The simultaneous treatment of these margins could significantly modify the quantitative and even qualitative results in a version of the analysis that takes into account geographic disaggregation by dividing the urban area into many subareas. As a minimum, a division into suburbs and central cities is needed. Geographic disaggregation would introduce a sixth margin: that of substituting proximal trip destinations for remote ones. In a geographically disaggregated setting, we would see how the consumers would change work and residence locations, and how the location of businesses would become endogenous in order to economize on rents and wages paid which would be altered by the pricing policies targeting car use. Such a geographically detailed model would be like an empirical version of the general equilibrium model of Anas and Rhee (2006), allowing a much more systematic analysis of the effect of urban spatial expansion on the fuel efficiency and emissions generated in an urbanized area. Most important is the fact that in a geographically disaggregated setting in which the areas are connected by a road network, the congestion toll would vary by road whereas the fuel tax rate would be a flat tax per liter (not varying by road or the geography). It would be interesting to see how the results would be modified in such a geographically disaggregated setting.

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