

A Model to Evaluate Vehicle Emission Incentive Policies in Japan

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ABSTRACT

Using three years of data from the 47 prefectures of Japan, we estimate behavior of households who simultaneously make discrete decisions about vehicle ownership and continuous decisions about driving distance. We use the estimated parameters to calculate elasticities and to simulate the effects of alternative policies such as a tax on gasoline, on distance, or on particular car characteristics. Given choices about cars and distance, we can also calculate emissions. We find that the demand for vehicle kilometers traveled (VKT) depends positively on income, and it depends negatively on the cost per kilometer. The demand for any particular type of vehicle also depends positively on income, and negatively on the cost of that vehicle. Since we model simultaneous choices by consumers, a tax on gas or distance can affect both the chosen distance *and* the chosen car. Similarly, a tax on particular cars can affect choices both about cars and about distance. What we find, however, is that car choices are relatively inelastic – either to taxes on cars or to taxes on gas or distance. Thus emissions are more affected by taxes on gasoline or on distance than by taxes on particular vehicles.

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The accumulations of carbon dioxide (CO₂) and other greenhouse gases (GHGs) are likely to lead to global warming and other significant climate changes in coming years, with possibly large future economic costs. The burning of fossil fuel also emits regional pollutants such as sulfur dioxide (SO₂), and local pollutants such as carbon monoxide (CO), nitrous oxides (NO_x), and hydrocarbons (HC) that react with sunlight to cause health-damaging urban ozone (O₃). The control of these emissions may be a politically complex issue in light of various national interests, problems with data, analytical issues, difficulties of international coordination, and high uncertainty.

Vehicles are a significant source of these pollutants: in 1997, vehicles contributed 31.5 percent of CO₂ emissions in the United States, and 20.9 percent in Japan.¹ The transportation sector is becoming more important as a polluter in recent years. In Japan, CO₂ emissions from the transportation sector have increased by 23.0 percent from 1990 to 1999. Emissions from trucks and public transit remained almost at the same level, so the majority of this increase is due to a rising number of passenger vehicles, a general increase in the size of these vehicles, and a rise in kilometers driven. In fact, 87.8% of the CO₂ emissions from the transportation sector were attributed to motor vehicles, and a formidable 56.4% of that is from passenger cars.² The same website predicts that the CO₂ emissions from transportation in Japan will reach 296 million tons in year 2010 if no action is taken to curb the emissions. Upon the adoption of the Kyoto Protocol, Japan has agreed that these emissions will fall below 250 million tons, about the same level as in 1995. Thus, Japan's transportation sector must cut CO₂ emissions by 46 million tons.

The costs of cutting these emissions are anticipated to be enormous, but Pigou (1920) suggests that these costs can be minimized by the use of incentives such as a pollution tax or permit system. A price per unit of emissions provides all the right incentives to reduce emissions by using all the cheapest avenues of abatement: switch to cleaner fuels, employ abatement technology, or reduce the usage of energy itself.

This theory works well for stationary sources such as electric power plants, where the technology is available to measure emissions in a reliable and cost-effective

¹ These statistics were computed from http://www.bts.gov/btsprod/nts/Ch4_web/4-49.htm for the U.S., and from <http://www.env.go.jp/policy/hakusyo/img/212/fb1.2> for Japan.

² <http://www.ecomo.or.jp/kankyo2001-2002/menu.html> provides statistical documentation.

manner. Some empirical studies have found that initial market incentive policies for electric power plants in the United States has significantly reduced the costs of SO₂ emission abatement (Schmalensee et al, 1998). However, the theory cannot be applied so easily to mobile sources where the measurement technology is simply not available.³

This paper investigates alternative policies such as taxes on gasoline or on cars that could help achieve efficient methods of vehicle emission abatement in Japan. What are the effects of each such policy on car choices and driving behavior, and what are the effects of those driving behaviors on emissions? To answer these questions, we use three years of data for the 47 prefectures of Japan to estimate the simultaneous determination of household discrete choice of vehicle and continuous demand for driving distance. We then use those estimates to simulate policies and to predict new behaviors. We use those outcomes to calculate emissions of CO₂ and local pollutants (CO, NO_x, and HC). We also find the equivalent variation measure of welfare cost, and we use it to plot the marginal cost of abatement (MCA).

What are the behaviors to be targeted? If emissions *could* be measured, and a tax per unit of vehicle emissions enforced, then drivers could: (1) buy a newer, cleaner car, (2) buy a smaller car with better fuel efficiency, (3) fix their broken pollution control equipment, (4) buy cleaner gasoline, (5) drive fewer kilometers, (6) drive less aggressively, and (7) avoid cold start-ups.⁴ Moreover, an emissions tax would induce consumers with different incomes or demographic characteristics to choose different combinations of these methods, as required for economic efficiency. Some owners of older vehicles may speed up their plans to switch to a newer or smaller car, while other drivers with easier access to public transportation may switch to no car at all. Still others may pay the tax instead of changing their habits, if they find their vehicles indispensable. As an alternative to such incentives, command-and-control regulations tend to ignore heterogeneity, requiring the same forms of abatement for all drivers.

³ On-board diagnostic equipment is too costly because millions of vehicles would need to be retrofitted (Harrington et al., 1994). Remote sensing is less expensive and can measure *average* emissions, but cannot distinguish emissions clearly enough to tax each car separately (Sierra Research, 1994, p. 17).

⁴ Because of cold start-up emissions, Burmich (1989) finds that a 5-kilometer trip has almost three times the emissions per kilometer as a 20-kilometer trip. Sierra Research (1994) finds that a car driven aggressively has CO emissions that are almost 20 times higher than when driven normally.

While the inability to measure emissions may preclude a per-unit tax on vehicle emissions, it does not necessarily preclude any use of such incentives. Price mechanisms can still be applied to any observable choice, especially to market transactions that generate an invoice for verification where the auto dealer or gas station can collect the tax or provide a subsidy. Heterogeneity is respected, allowing each individual to make decisions about choice of vehicle and kilometers.

In fact, incentive instruments have been at the center of recent discussions about environmental policies in Japan.⁵ The Japanese government charges annual registration fees that can be made to depend on vehicle characteristics, and periodic inspections can record odometers for a tax on distance. These policies may also contribute positively towards other goals such as the reduction of traffic congestion.

A few papers have previously explored market incentives that could be used in place of a unit tax on vehicle emissions.⁶ Several other papers have estimated models of discrete choice among vehicle types.⁷ Some models in the existing literature have estimated the demand for gasoline or for vehicle-kilometers traveled (*VKT*) as functions of relevant prices and incomes, and some other models have predicted emissions.⁸ The major contribution of our research is to include all of these choices simultaneously. This simultaneity is important, because it allows us to model how the cum-tax price of gasoline affects not only choices about gasoline expenditures and kilometers driven, but also choices about whether or not to own a car. Similarly, any exogenous change in the cost of a particular type of vehicle affects each household's choices both about cars and

⁵ See, for example, "The Report of the Study Group on Economic Instruments in Environmental Policies," at <http://www.env.go.jp/en/rep/tax/ishitax.pdf> (1998). The trading of permits may not work for millions of drivers, so we consider taxes or subsidies to drivers. A new higher gas tax may be politically unlikely, yet it is still worthwhile to explore its effectiveness as an emissions-reduction tool. Even if governments are unlikely to use tax-collected revenues for the various subsidies we study here, these incentives might instead be provided to drivers by private companies that desire to purchase "offsets"—reductions in vehicle emissions that offset the emission increases from stationary sources. For all of these reasons, we find it important to study specific incentives for drivers.

⁶ For examples, see Eskeland and Devarajan (1996), Innes (1996), Kohn (1996), Plaut (1998), Sevigny (1998), and Fullerton and West (2000, 2002). Fullerton and West (2000) simulate the effects of incentive policies with heterogeneous households, but they do not model discrete choices. Their parameters for the simulations are calibrated rather than estimated.

⁷ For examples, see McFadden (1979), Train (1986), Brownstone et al (1996), Goldberg (1998), Brownstone and Train (1999), and other papers reviewed in McFadden (2001).

⁸ See the review of this literature in Harrington and McConnell (2003). For an example of emissions models, the U.S. Environmental Protection Agency (U.S. EPA, 1998, pp.3-68) discusses the use of EPA's MOBILE5a model or California's EMFAC7F model.

about kilometers traveled. We retain heterogeneity at the household level, which is important because the same policy may affect different households differently.

Dubin and McFadden (1984) show how to combine a discrete choice model (for household appliances) with a continuous choice model (amount of electricity) in a sequential estimation framework. Goldberg (1998) and West (2004) apply their model to discrete choice of vehicle and continuous choice of distance. In this paper, we extend those models to allow *simultaneous* estimation of household decisions about cars and kilometers. We estimate the model using three years of data from the 47 prefectures, accounting for the existing gasoline and car taxes in Japan. We use the estimated model to simulate the effects of adding further tax on gasoline, on distance driven, or on cars (such as a tax that is proportional to each car's emission rate). For each policy, we calculate resulting emissions and welfare effects. Using demands derived from utility maximization allows us to solve back for the change in each household's utility, and the equivalent variation. Our results suggest that a tax on gasoline or distance has a weak effect on vehicle choice and thus on emission *rates*, but strong effects on the chosen distance and thus on total emissions. A tax on specific car types has weak effects both on car choices and on distance. It therefore has weak effect on emissions.

The rest of this paper is organized as follows. Section I develops the multinomial logit model used to estimate the discrete choice of vehicle bundle, and the continuous demands for vehicle kilometers traveled (*VKT*). Section II describes the data, and Section III presents the estimation results. Section IV discusses how seven alternative environmental policies may lead to reductions in emissions, and it simulates these policies using the estimated parameter values. Section V concludes.

I. Model

Our basic framework derives from a model in Dubin and McFadden (1984), where they conduct the estimation in two steps: first they apply a logit model to estimate the discrete choice, and then conditional on that choice, they estimate a continuous demand. Compared with the Dubin-McFadden model, our framework has two distinguishing characteristics. First, since we do not have micro-level data showing individual choices, we have to deal with aggregate data for each of the 47

prefectures in Japan. Second, we build a model to estimate simultaneously the discrete choice of vehicles and continuous demand for distance.

Assume that a total of K types of vehicles are available from which individual households can choose. In our empirical work below, we consider $K=5$ to include four vehicle types and the no-car option. For a household making choice i , direct utility is a function of vehicles kilometers traveled (VKT) and another consumption good c , that is, $U(VKT_i, c_i)$. Given income y , the budget constraint is given by:

$$\frac{p_g}{KPL_i} VKT_i + c_i = y - \rho k_i, \quad (1)$$

where p_g is the price of gasoline (in yens per liter), and KPL_i is fuel efficiency (in kilometers per liter), so that $p_i \equiv p_g/KPL_i$ is the price per kilometer in car type i . The price of the other consumption good is normalized to 1. The vehicle's annual rental cost is assumed to take the form ρk_i , where k_i is the total capital value of choice i (depreciated or market value), and ρ is the annual rental rate (which includes interest cost and further depreciation). We assume that $\rho = 0.25$ (but we also try other values and find almost no difference in results below).⁹ The indirect utility from choice i is a function of household income and prices, and it is denoted as $V(y - \rho k_i, p_i)$.

One common way to obtain the indirect utility function is to use a parametric VKT demand equation and then solve a partial differential equation from Roy's identity (Hausman, 1981). We use a log-linear specification for each VKT equation:

$$\ln(VKT_i) = \alpha_0 + \alpha_{1i} p_i - \beta(y - \rho k_i) + x' \gamma + \eta \quad (2)$$

where x is a vector of other observed socio-demographic variables that may affect VKT . Note that the index on α_{1i} means that an increase in the price of gasoline (and thus p_i) could affect desired distance in some cars more than in others. If it discourages driving in large cars and households can substitute, it could even *increase* distances in small fuel-efficient cars. The random error η represents agent-specific unobserved factors that may affect both the vehicle choice and the demand for VKT . It is assumed that $E(\eta) = 0$.

⁹ The 25 percent rental rate is consistent with a 5 percent annual interest cost plus a 20 percent depreciation rate (which we use later to calculate the current value of each car, k_i).

As pointed by Dubin and McFadden (1984), the conditional expectation $E(\eta/\text{bundle } i)$ does not have zero mean. This point can be seen clearly if we rewrite (2) into a more convenient form:

$$\ln(VKT_i) = \alpha_0 + \sum_j \alpha_{1j} p_j d_{ij} - \beta \sum_j (y - \rho k_j) d_{ij} + x' \gamma + \eta \quad (3)$$

where d_{ij} is the choice indicator variable equal to one when $i=j$. The random error η is correlated with d_{ij} . Taking the expectation of (3), we have:

$$\ln(VKT_i) = \alpha_0 + \sum_j \alpha_{1j} p_j S_j^* - \beta \sum_j (y - \rho k_j) S_j^* + x' \gamma, \quad (4)$$

where S_j^* is the predicted probability that the j th bundle is chosen. Equation (4) is called the ‘‘Reduced Form Method’’ in Dubin and McFadden (1984).

Next, using Roy's identity, the implied indirect utility function is given by:

$$V_i = \frac{1}{\beta} \exp(-\alpha_{0i} + \beta(y - \rho k_i) - x' \gamma - \eta) - \frac{1}{\alpha_{1i}} \exp(\alpha_{1i} p_i) \quad (5)$$

We assume that the individual chooses the vehicle type i that yields the highest indirect utility V_i . Observed vehicle choices then can be used to estimate the parameters of (5). However, note that the parameters of the vehicle choice in (5) are the same parameters as in the distance choice in (4).¹⁰ Indeed, for many households, the choice of vehicle and desired distance are interrelated. For this reason, we use equations (4) and (5) together to obtain estimates of parameters that best characterize the simultaneous choice of consumers regarding vehicles and distance.¹¹ Now the index on α_{1i} means not just that an increase the price of gasoline (and thus p_i) can differentially affect distances in each type of car, but that it can have different effects on the choice of car. The gas price can decrease demand for large cars and *increase* demand for small, fuel-efficient cars.

To proceed, we next add a choice-specific error term ε_i to equation (5). As in the usual discrete choice model, this error term represents the difference between the

¹⁰ An exception is that utility in (5) allows for constant terms α_{0i} that depend on choice i , to reflect unobserved differences that affect utility but are not captured by p , y , or x . These constants also differ from α_0 in equation (4), to capture scale differences between utility and $\ln(VKT)$. As described below, the vehicle bundles include a no-car option, and we normalize the indirect utility from this bundle to zero.

¹¹ We do not know of any papers that have estimated the discrete choice in (5) and the continuous choice in (4) simultaneously. They are estimated sequentially by Dubin and McFadden (1984) for appliances and electricity, and also sequentially by Goldberg (1998) and West (2004) for vehicles and distance.

true individual utility at choice i and the calculated utility level. In practice, this error term for each choice i , conditional on individual-specific error term η , is assumed to be independently distributed over choices with an extreme value distribution. Using this extreme value distribution, we can solve for the predicted probability of choosing bundle i at prefecture n , called S_{in}^* (the first term on the RHS of equation (6a) below). Then we add an error u_{in} to reflect the difference between the predicted probability of choice i and the observed share for choice i (S_{in}). In combination, we can then estimate simultaneously the following moment conditions:

$$S_{in} = S_{in}^* + u_{in} = \int \frac{\exp(V_{in}(\eta))}{\sum_j^K \exp(V_{jn}(\eta)) + 1} f(\eta) d\eta + u_{in} \quad (6a)$$

$$\ln(VKKT_{in}) = \alpha_0 + \sum_j \alpha_{1j} p_{jn} S_{jn}^* - \beta \sum_j (y_n - \rho k_{jn}) S_{jn}^* + x'_n \gamma + v_{in} \quad (6b)$$

Here, v_{in} represents the difference between observed and predicted kilometers traveled. Both u_{in} and v_{in} are assumed to be independent across different choices and across different prefectures. We estimate (6) using Generalized Method of Moments (GMM), as described more below.

Once we obtain the parameter estimates, we are ready to calculate elasticities for both discrete choices and continuous demand. Let z_i denote either k_i or p_i . Then, the own- and cross- elasticities for the discrete choice model are given by:

$$\text{Own elasticity:} \quad E_{iz_i} = \frac{\partial S_i}{\partial z_i} \frac{z_i}{S_i} = \frac{\partial V_i}{\partial z_i} z_i (1 - S_i), \quad (7a)$$

$$\text{Cross elasticity:} \quad E_{iz_j} = \frac{\partial S_i}{\partial z_j} \frac{z_j}{S_i} = -\frac{\partial V_j}{\partial z_j} z_j S_j. \quad (7b)$$

Note that the right-hand-side of (7b) does not depend on i , so variable j has the same cross-elasticities for all choices $i \neq j$. For example, a change in the distance price p_j has the same cross-price effect on the other four vehicle choices. The elasticity of choice i with respect to income is given by:

$$E_{iy} = y \left(\frac{\partial V_i}{\partial y} - \sum_j S_j \frac{\partial V_j}{\partial y} \right) \quad (8)$$

For the continuous distance demand, the formula for the own-price elasticity is:

$$e_{p_i} = \frac{\partial \ln(VKT_i)}{\partial \ln p_i} = \alpha_i p_i \quad . \quad (9)$$

We can also calculate the income elasticity e_y and capital cost elasticity e_{k_i} , as:

$$e_y = \frac{\partial \ln(VKT)}{\partial \ln y} = -\beta y, \quad e_{k_i} = \frac{\partial \ln(VKT)}{\partial \ln k} = \beta \rho k_i. \quad (10)$$

In equations (7) – (10), each elasticity is typically evaluated at the mean values of y and k and at the average price per kilometer for each choice.

II. Data

A. General Data Description

In order best to analyze the behavior of households choosing automobile bundles and VKT , we could use household-level micro-data on each household's characteristics, income and expenditures, vehicle ownership, kilometers driven, and each vehicle's characteristics including fuel efficiency in kilometers per liter (KPL), local emissions per kilometer (EPK), and carbon dioxide emissions per kilometer (CPK). No single data set contains all such information for Japan.

The Family Income and Expenditure Survey (FIES) conducted by the Ministry of Public Management, Home Affairs, Posts and Telecommunications of Japan provides some data on income, expenditures on gasoline, car purchase, and other private transport-related costs, as well as the price of gasoline and the purchase price of cars (but it contains no distinction among the cars' attributes).¹² However, the desirable household-level micro-data containing household characteristics and household accounting are not disclosed to any party outside the nation of Japan. We must use the publicly available aggregate data, "The Annual Reports on the Family Income and Expenditure Survey," published by the Statistics Bureau of Japan. Since the aggregate data are available for each prefecture, we treat the 47 Japanese prefectures as units of observation, for each of the three years 2000-2002. That is, each observation describes the *average* household in a particular prefecture in a particular year, so we think of each

¹² See <http://www.stat.go.jp/english/data/kakei/1560.htm> for an outline of the FIES.

prefecture as a single household in the sample. We pool the data for three years to obtain a sample size of $47 \times 3 = 141$ observations.

B. Classification of Vehicle Bundles

In our model, an agent representing an individual household faces a discrete choice among a finite number of vehicle bundles. Each vehicle bundle is identified by the vehicle's type according to size and vintage. In particular, we define our vehicle types according to the engine size measured in liters of total displacement, as is customary in the Japanese classification of passenger cars. The *regular* passenger car class (denoted by subscript r) consists of cars with total displacements of 2.000 liters and above, and the *small* passenger car class (denoted by s) consists of cars with total displacement less than 2.000 liters.¹³ The vehicle vintages are classified by *new* cars (denoted by n) versus *old* cars (denoted o). Vehicle bundles are then described by a set of subscripts $\{rn, ro, sn, so, 0\}$, where 0 denotes the zero-vehicle bundle.

C. The Data Sources

(1) *Household income and expenditures on gasoline.* We use the FIES data to obtain the prefectural average of expenditure on gasoline and total expenditures (which we use as total income). The FIES data for a given year are collected through a survey of randomly selected households throughout all of Japan. The selection of these households is based on a three-stage stratified sampling method, where the sampling units at the three stages are the municipality, the survey unit area, and the household. Each prefecture's capital city is a stratum, and for some reported data series, the sample of the survey consists solely of households in the capital city, not the entire prefecture. This is not a problem, since we must in any case assume that all households of a given prefecture behave similarly. Some statistics reported in the Annual Reports are based on surveys among Workers' Households, and some others are based on All Households. We use the Annual Report for years 2000, 2001, and 2002, supplemented by some series taken from the Reports for years 1999.

¹³ Japan has another class, *light vehicle*, consisting of passenger cars with total displacement less than 0.660 liters. This class is dropped from our study because it does not exist in the U.S., and so no data are available for its emissions. The next section describes our U.S. sources for emissions data. Of passenger cars in Japan, light vehicles were 17 percent in 1999, 19 percent in 2000, and 20 percent in 2002.

(2) *Household Characteristics*. Since the demographic characteristics of households are not available from the Annual Reports of FIES, even at the aggregate prefecture level, we must rely on the 2000 Population Census, which is the most recent census conducted in Japan. These data are entirely public, and can be obtained freely from web pages through <http://www.stat.go.jp/english/data/kokusei/index.htm>. For each prefecture, we obtain from the Census the average family size, average age of household heads, average number of income earners per household, fraction of residents with higher-education, fraction of residents under 15 years of age, fraction of households residing in densely inhabited districts, homeowner fraction of households, dual-income fraction of households, and the fraction of households with the primary income earner commuting more than 90 minutes per day. Table 1 has the mean values of our demographic variables.

(3) *Household-Owned Vehicle Characteristics*. Unfortunately, detailed characteristics of household-owned vehicles are not observable, including make, model, year, vehicle vintage, and number of cylinders. Since prefectures are the units of observation, our estimations require at least the information on what fraction of households owns each automobile bundle in each prefecture (including the choice of not owning a vehicle). The Automobile Statistics Data Books published yearly by the Japan Automobile Dealers Association (JADA, 2000, 2001, 2002) quantifies registered vehicles by type and by prefecture. It also quantifies new cars purchased of each type in each prefecture.¹⁴ We define all new cars purchased of each type through years 1999 and 2000 as the quantity of *new* (vintage type *n*) cars held by the households in year 2000 (for each size category). Subtracting this quantity from the number of registered vehicles of each size in year 2000, we obtain the quantity of *old* (vintage type *o*) cars of each size. Vehicle quantities for 2001 and 2002 are obtained similarly. Because these statistics from the JADA Data Books are essentially for the households who own at least one automobile, we supplement them by the reported percentage of households owning no vehicle.¹⁵

¹⁴ The quantity of new cars purchased is not reported in the Data Books, but JADA personnel testify that the reported number of first-time registration of new cars represents this quantity.

¹⁵ For this purpose, we use a report on the passenger vehicle market by Japan Automobile Manufacturers Association (JAMA, http://www.jama.or.jp/release/news/prev/2000/03/000329_t1.html). These figures, however, are not available by prefecture.

(4) *Fuel Efficiency of Vehicles.* To our knowledge, no source in Japan provides data on fuel efficiency and emission rates (except for brand new cars). Since we need test results for older cars, we use data on cars in the U.S. to approximate fuel efficiency and emissions of cars in Japan. Technologies are similar in the two countries, and cars made in Japan are sold in the U.S., suggesting that a sample of Japanese cars found in the U.S. should be a good proxy for a sample of cars available to Japanese consumers.

We use the results of recent vehicle testing by the California Air Resources Board (CARB, 1997, 2000) in the United States to estimate *KPL* for each size-vintage bundle. The dataset consists of two sub-samples: first, in “series 13”, the CARB tested a total of 345 passenger cars, light-duty trucks, and medium-duty vans from November 1995 to March 1997; and second, in “series 14”, the CARB sampled 332 vehicles from November 1997 to August 1999. Each observation in the CARB data represents an individual tested car and contains the manufacturer, year, and model, along with fuel efficiency (measured in miles per gallon, *MPG*). We then identify and extract the subset of tested cars consisting of cars made by Japanese manufacturers (Toyota, Nissan, Mazda, Mitsubishi, Honda, Isuzu, and Subaru). The extracted subset is a sample of 234 Japanese vehicles. We then divide this subset into our two engine size categories, which leaves us with 96 regular-size cars and 138 small-size cars. For each set, we estimate *MPG* as a function of vehicle age (in years) using a semi-log specification.¹⁶ The estimation results are shown in the first panel of Table 2.

The result confirms that for both types of cars, fuel efficiency declines with vehicle age. We can evaluate the estimated regression at any particular age to get predicted *MPG*. For new cars, we take $age=1$ for both types in all years. For old cars, we use the reported mean of age of each type of passenger car in Japan for each year.¹⁷ Averaging over all three years, the estimated fuel efficiencies are: $MPG_m=21.9$, $MPG_{ro}=21.1$, $MPG_{sn}=29.0$, and $MPG_{so}=27.5$. We multiply these figures by 0.4251 to convert to *KPL*, listed in Table 3.

¹⁶ Even if a given car has the same *MPG* in Japan as in the U.S., however, the mix of regular-size cars (>2.0 liters) in the U.S. may differ from the mix of such cars in Japan. Thus the *MPG* of regular cars in Japan could differ from the *MPG* predicted from this regression on Japanese cars in the U.S.

¹⁷ These data are provided by the Automobile Inspection and Registration Association (AIRA) of Japan (<http://www.aira.or.jp/data/pdf/age.pdf>). For years 2000, 2001, and 2002, respectively, the average age for regular-size cars is 4.8, 5.2, and 5.6 years; for small-size cars the average age is 6.3, 6.5, and 6.6 years.

(5) *Data on Emissions of Local Pollutants.* The critical data on emissions per kilometer (*EPK*) of individual cars tested in Japan are unavailable.¹⁸ The CARB data provide test results on the emissions rates per mile (*EPM*) of carbon monoxide (CO), nitrous oxides (NO_x), and hydrocarbons (HC's) for each tested vehicle. Moreover, we can calculate the weighted sum of these emissions:¹⁹

$$EPM = 0.1 * CO + 0.495 NO_x + 0.405 HC. \quad (11)$$

We use the sample of 234 Japanese cars described in the previous subsection. For each type, we estimate an equation for *EPM* as a function of vehicle age, using the semi-log specification. The second panel in Table 2 reports the estimation results.

To obtain the emission rate for each vehicle bundle, we evaluate the estimated emission rate regressions at *age*=1 for new cars, and at the reported means of the age of passenger cars in Japan for old cars for each year 2000 through 2002. Table 3 lists the means of the rates calculated for emission per kilometers (*EPK*). These vary from .216 for a new regular-size vehicle to .549 for an old small-size vehicle. Surprisingly, for either age category, the larger cars have lower emission rates than the smaller cars.

(6) *Data on carbon dioxide emissions.* While the data on CO₂ emissions per kilometer (*CPK*) of individual cars tested in Japan are unavailable, the aforementioned “series 14” of the CARB data provides test results on the carbon dioxide emission rate per mile (*CPM*). We extract and obtain a sample consisting of 117 cars made by Japanese manufacturers. We then divide it into our two engine size categories, which leaves us with 48 regular-size cars and 69 small-size cars. For each set, we estimate *CPM* as a function of vehicle age (in years) using a semi-log specification. The estimation results shown in the last panel of Table 2 reveal that the carbon emission rate does not depend much on age, but it does depend on size. When we use those estimates to calculate carbon dioxide per kilometer (*CPK*), Table 3 shows that the mean for regular size cars is about 250 and small cars is about 190 (grams/km).

¹⁸ For brand new cars, the 10:15- or 11- Mode tests are performed by manufacturers to meet the established emission standards and to release their models' environmental specifications. For older vehicles, however, no emissions test is done in Japan that is equivalent to that by the CARB. Japan Automobile Research Institute (JARI), a public-service and test-research organization, has handled a few cases of emissions testing on used cars. Unfortunately, the data from those cases cannot be disclosed.

¹⁹ See Fullerton and West (2000) for discussion of these weights.

(7) *Gasoline prices.* As described above, the FIES provides each year's average price of gasoline for each prefecture (in yens per liter). These are observed gasoline prices and include the existing gasoline tax. The per-unit gasoline tax rate is uniform across the nation of Japan. The bottom of Table 1 shows the mean gasoline price across prefectures (as well as mean gasoline expenditure and total expenditure).

(8) *Average Market Value of Vehicles.* Although the Annual Reports on the FIES offer the prefectural averages of purchase prices of all cars (with no distinction by the cars' attributes), we need to have a market value for each of the four vehicle bundles (for capital cost, k_i). For new cars, we can use the manufacturers' suggested retail prices of selected models available on multiple Japanese manufacturers' websites. Using the list of the ten most popular models published in the JADA Data Book per year, we obtain each k_{rn} and k_{sn} as the weighted average of the retail prices of the subset of these models belonging to each size class, with the weight being the share of each model. We assume that cars depreciate at a rate of 20 percent per year, so used car prices k_{ro} and k_{so} are calculated as:

$$k_{ro} = k_{rn} \times 0.8^{aar}, \quad \text{and} \quad k_{so} = k_{sn} \times 0.8^{aas},$$

where aar is the average age of regular cars, and aas is the average age of small cars in each year. That year's market value for any vehicle bundle is thus obtained, but it does not vary across prefectures. Table 3 lists this market value of each bundle.²⁰

(9) *Operating cost of each bundle per kilometer.* For each vehicle bundle, we combine each year's prefectural data on gasoline price (yens per liter) and each year's fuel efficiency in kilometers per liter (KPL_i) to calculate that year's operating cost in yens per kilometer (p_{in}). Here, we assume that gasoline expenditures are the only operating cost per kilometer.²¹ For each vehicle bundle, the bottom of Table 3 shows the mean and standard deviation of this cost per kilometer, over 47 prefectures.

²⁰ Other fixed costs may vary across vehicle types, including insurance, finance charges, and license fees. Following West (2004), we assume that market value serves as a good proxy for overall fixed costs because those other costs vary closely with market value.

²¹ Some maintenance cost may generally add to this cost, but we have no clear way to divide maintenance cost into the part that is required regardless of kilometers and the part that should be treated as a cost per kilometer. West (2004) adds tire cost per kilometer to the calculation of per-kilometer costs. Expenditures on tires, unfortunately, are not reported for Japanese households.

(10) *Vehicle Kilometers Traveled (VKT)*. Since *VKT* is not observed directly, we use data on E_n , the average household's expenditure on gasoline in prefecture n . We take E_n (in yens per household) and divide by p_{in} (in yens per kilometer) to get *VKT* (in kilometers per household). Thus, the dependent variable on the left side of (6b) becomes $\ln(E_n) - \ln(p_{in})$.

IV. Estimation Results

We have information on each prefecture's shares $\{S_{rn}, S_{ro}, S_{sn}, S_{so}, S_o\}$, but the sum of these five shares is one. To avoid the problem of collinearity, we use only the first four shares to form four moment conditions based on (6a). Since p_{in} vary across the four vehicle types, we have four additional moment conditions that are based on continuous demand for *VKT* in (6b). We employ GMM to estimate our model on these eight moment conditions. Estimating (6a) requires some distribution of the random error η , so we assume η to be distributed in standard normal. The estimation results are reported in Table 4.

In Table 4, the first five parameters are the key parameters in our paper, and all five are significantly different from zero. The coefficients on per-kilometer gas prices $\{\alpha_{li}\}$ are all negative and highly significant. Thus, for each car choice, people drive less when they face a higher per kilometer cost of driving. The coefficient on income or total expenditure (β) is negative, so people drive more when they have more income (net of the capital cost of their vehicle). Note Equation (6b), where total expenditure enters the demand for *VKT* with a negative sign in front of it. Table 4 also indicates that distance demand is greater for households that own their own homes, are younger, have more children, and live outside a metropolitan area. Note that these interpretations are tricky, however, because these parameters serve dual roles: they determine distance choices *and* discrete car choices.

Our primary interest is to understand how people respond to changes in the gas price per kilometer, total expenditure (income), and capital cost. To analyze these questions, we calculate the elasticities using the formulas derived above, for both discrete choice and continuous demand. Table 5 lists own- and cross- elasticities for the discrete choices with respect to gas price per kilometer. Table 6 lists all own- and cross- elasticities for the discrete choices with respect to each capital cost (k_i) and the

elasticity of each choice with respect to income (y). Finally, Table 7 shows all continuous *VKT* demand elasticities.

In Table 5, for the gasoline price in any row, the table shows the effect on each vehicle bundle choice, that is, the change in the probability of choosing that column's car for a one percent change in gas cost per kilometer in that row. The diagonal of Table 5 shows the own-price elasticities. As expected, the own-elasticity for each choice is negative, while the cross-price elasticities are positive for all car types. In other words, an increase in the gas price of the car in any row of the table would decrease the market share of that same car but increase the market share of other cars. Given a car size (*regular* or *small*), the own-elasticity of the new car choice is much smaller than that of the old car (in absolute value). That is, household choice to own an old car is more negatively affected by the gas price than is the choice to own new car. For example, a one-percent increase in the gas price of choice *sn* induces a 0.69 percent decrease in the probability of choosing *sn*, while the same change to the gas price of choice *so* induces a 2.7 percent decrease in the probability of that choice. Note that a gas price change for choice *m* barely alters any market share.

The first part of Table 6 presents capital cost elasticities for the discrete choice model. Each elasticity gives the percentage change in market share of the column car associated with a one-percent increase in the capital cost of the row car. As expected, all own- elasticities are negative while cross- elasticities are positive for all car types. Thus an increase in the capital cost of a car would decrease the probability of owning that same car, and increase the probabilities of owning each other car (or no car). Quantitatively, however, all entries are close to zero; any change in capital cost barely affects the market share of any choice. The second part of Table 6 reports the share elasticities with respect to income (total expenditures). The last entry for the no-car option is negative, suggesting that an increase of income makes households less likely to hold no car, as expected. The other entries have different signs; more income increases the share of small old cars and decreases other shares.

Table 7 shows effects of those key variables on *VKT*, given each car choice. Goldberg (1998) calls these "short run" elasticities, because the household can change its distance but not its car. The short run elasticity of *VKT* with respect to gas price per kilometer is negative for every choice. The *VKT* elasticity for small old cars is in the

range of previous estimates (-0.555), but the elasticities for the other three car types are substantially higher (-2.4 to -11.2). Perhaps these estimates are "too high" and unreliable because we estimate a structural model and because we are limited to data for prefectures rather than for individual households. Yet perhaps other prior results are "too low" and unreliable because they do not capture the simultaneity of car and distance choices by households, as we do here. We still have no "final" results, but we believe that results here are important indicators that we need further investigation.

In any case, the *relative* elasticity values are instructive. Given car size, for example, Table 7 shows that *VKT* demand is more responsive to a change in gas price for new cars than for old cars. For regular cars in the first two rows, the *VKT* elasticity is -2.378 if old and -11.23 if new. For small cars in the next two rows, the elasticity is -0.555 if old and -2.383 if new. For a different comparison, taking vintage as given, *VKT* demand is substantially more responsive to a change in the gas price for regular-sized cars than for small cars. If old, this elasticity is -0.555 for small cars and -2.378 for regular cars. If new, it is -2.383 for small cars and -11.23 for regular cars. An explanation can be found in Table 3, where a regular sized car is shown to be less fuel efficient than a small car. If they are both of the same vintage, a unit increase in the gasoline price of a regular car affects the distance driven more than does an increase in the gas price of a small car.

The form of our model in equation (5) and our negative estimated β together imply that income has a positive effect on indirect utility – as expected. Thus, more income increases the probability of owning a car in Table 6, and a higher capital cost k_i reduces the probability of owning that car – as expected. In our model of simultaneous discrete and continuous choices, however, equation (10) shows that *VKT* elasticities are $e_y = -\beta y$ and $e_{k_i} = \beta p k_i$. Thus, the same estimated $\beta < 0$ means that more income must raise *VKT* demand, and a higher capital cost must reduce *VKT* demand. As shown in Table 7, a household drives 0.23 percent more when its income rises by one percent, but it reduces driving by less than 0.04 percent when any capital cost rises by one percent.

IV. Simulations of Various Environmental Policies

We now use the estimated parameters to perform a number of simulations to compare the effects of alternative policies. For any particular policy, we can use the

characteristics of the Japanese population along with the estimated parameters to predict the proportion of households that hold each vehicle, the total distance driven, and total emissions. The benchmark for comparison is the status quo. Our estimates already incorporate current policies, because the data on gasoline prices reflect existing taxes, and the purchase prices of vehicles include the vehicle acquisition taxes currently levied by the Japanese government.²² For the current policy regime, the simulated household average *VKT* is 4,029 kilometers per year. The average household has local emissions of 1.914 kilograms and CO₂ emissions of 819 kilograms.

For each vehicle, note that *VKT* in equation (4) and utility in equation (5) both depend on the operating cost per unit distance (p_i) and the cost of the vehicle (k_i). Therefore each policy needs to be translated into its “model-equivalent form,” that is, some particular change in either p_i or k_i . In this paper, we focus on one policy at a time rather than combinations of multiple policy instruments.

A. Policies That Alter the Cost per Kilometer Driven

First, we consider policy options that affect p_i , including a tax per liter of gasoline (t_g), a tax per unit distance (t_d), or even the possibility of a tax per unit of local pollutant emissions (t_e) or carbon emissions (t_c). To incorporate any such policy, the new general form for the cost per kilometer for choice i is:

$$p'_i = \left[\frac{p_g + t_g}{KPL_i} + t_e EPK_i + t_c CPK_i + t_d \right] \quad (12)$$

For these purposes, the existing gasoline tax is embodied in p_g , so any tax rate in (12) represents an added tax. We next describe our simulations.

1.) A tax per unit of local emissions ($t_e > 0$, $t_c = t_g = t_d = 0$). A tax in yens per gram of emissions times *EPK* in grams per kilometer yields the effect on the price in yens per kilometer. As discussed above, this policy is not available if emissions are too difficult or costly to measure. Emissions are not a market transaction with an invoice to verify the tax base for purposes of collection and enforcement. However, the concept of taxing each unit of emissions has been shown to minimize the total social cost of

²² The current acquisition tax on a passenger vehicle is five percent of the “acquisition price”, regardless of whether the car is new or used. The “acquisition price” of a vehicle for purposes of this tax is determined by the retail price of the model when sold brand new and the age of the particular vehicle.

achieving any given emissions-abatement target, and it thus represents an important ideal against which to compare all of the other more-realistic policy options. We assume that consumers know how their vehicle choices affect their emissions rate and thus tax due, so this policy may induce households to choose cleaner-burning cars as well as to drive less.

2.) A tax per unit of CO₂ emissions ($t_c > 0, t_e = t_g = t_d = 0$). This policy may be somewhat more feasible than the tax on local pollutants, because it can be imposed by taxing the carbon content of each fuel when purchased. Carbon emissions are closely related to the carbon content of fuels, whereas local emissions per unit fuel depend on characteristics of the vehicle.

3.) A tax per liter of gasoline ($t_g > 0, t_c = t_e = t_d = 0$). This policy is technically feasible and enforceable, as the Japanese government currently collects such a tax.²³

4.) A tax per kilometer driven ($t_d > 0, t_c = t_g = t_e = 0$). The car's driving distance is not purchased in a market transaction, but kilometers driven are certainly more observable than emissions. Old style odometers might be rolled back by consumers who want to cheat, but new cars have electronic odometers that are more difficult to change. If each car is inspected once a year, even just for the usual safety inspection, the inspector can record the distance, and the prefecture can include the calculated tax in the annual registration fee. In theory, the distance tax ought to perform better than a gas tax, because it avoids the "rebound effect" discussed in Harrington and McConnell (2003). A gas tax might induce consumers to buy more fuel-efficient cars, so the higher KPL_i partly offsets the higher price per kilometer, but a distance-tax cannot be avoided in any way except by reducing driving distance. However, the distance-tax would not reduce emissions as much as the emissions tax, because it does not encourage any of the other abatement methods that would change EPK_i .

For all of these tax rates, we infer a reasonable range from the current gasoline tax rate in Japan, 53.8 yens per liter. To implement an added tax that is 5 to 100 percent of the existing gas tax, we choose the range of $t_g = 2.69$ to 53.8 (¥/liter), as shown in the second row of Table 8. We then we find how much on average (across vehicle choices)

²³ Both the national government and prefectural governments levy taxes on gasoline. The rates are currently 48.6 yens/liter (national) and 5.2 yens/liter (prefectural).

each gas tax rate adds to the per-kilometer price of driving (Δp in the first row). We use that Δp to calculate the comparable range for t_e , t_c and t_d (shown in rows 3 to 5).

For any tax, we use equation (12) to get the new price per kilometer for each vehicle, and we use those in conjunction with the estimated parameters to calculate the new choices of vehicle types, distances traveled, and the resulting total emissions. Figures 1-3 show simulated effects on *VKT*, local emissions, and CO₂ emissions.

Figure 1 shows effects on *VKT* of the four taxes when they are scaled to raise the per-kilometer cost by the same amount on average. A tax on local emissions (in yens/gram) reduces vehicle distances the most, followed by the distance tax (per km), the gasoline tax (per liter), and the CO₂ tax (per gram). The solid dark line shows that doubling the existing gas tax will achieve about 40 percent reduction in *VKT*, whereas a tax of 14 yens per gram of local pollutants will raise the price per kilometer the same amount (Table 8) and reduce driving distances by 55 percent (Figure 1).

Figure 2 shows the control of local emissions achieved by these comparable rates of tax on gasoline, distance, and emissions. The points where each curve crosses the horizontal line labeled "-30" indicate that government can cut local pollutants by about 30 percent of the status-quo level by charging an extra 2.3 yen per km through t_e , or an extra 3.3 yen per km through t_d . To bring about the same 30 percent reduction in emissions using the gasoline tax as the only instrument would require an extra 3.6 yen per km (an increase of almost 70 percent in the existing gas tax). Similarly, Figure 3 shows the degree of carbon dioxide abatement achieved by these taxes, when they are scaled to increase per-kilometer costs by the same amount.

Each Figure 4 through 7 shows the effects of a tax on all five vehicle ownership shares. In all four figures (for all four taxes), households shift away from using a small, old car (type *so*). This car has the largest emission rate, as seen in Table 3. All other choice shares rise. The choice that rises the least in all four figures is the one with the next highest emission rate (type *ro*, which also has the lowest fuel efficiency in Table 3). Thus, all four taxes tend to encourage newer cars. The local emissions tax in Figure 4 and carbon tax in Figure 5 raise the *ro* share only slightly, whereas the gasoline tax in Figure 6 and the distance tax in Figure 7 raise the *ro* share almost as much as the other shares. These latter two taxes encourage the no-car option the most.

B. Policies That Alter the Cost of Each Vehicle

We now consider potential policy instruments to alter the capital cost or rental cost of some car types. Examples of such policies are taxes levied at the time of vehicle purchase (acquisition taxes), annual registration fees, or annual vehicle tax. The annual fixed cost for owning choice i is now raised by t_i , the bundle-specific addition to the rental cost, in 100,000 yens, for $i = \{rn, ro, sn, so\}$. We can then compare our simulation results with the corresponding benchmark outcomes.

1.) A tax on the size of the engine (t_s). The correlation between the size of the engine and the emissions rate is ambiguous.²⁴ Surprisingly, the calculation of *EPK* using local pollutants from the CARB data reveals that small cars have a *larger EPK* than regular cars (see Table 3). Whether this results from the specific nature of the CARB data remains unclear. It is well established, however, that size increases emissions of the major greenhouse gas (CO₂), as is also shown using the CARB data (see Row 5 in Table 3). As expected, old cars have a larger *EPK* than new cars.

Japanese prefectures already collect annual fees on vehicles that rise with total displacement of engines, and so further taxation of size can be implemented easily.²⁵ A tax on engine size can be modeled by the addition of $t_{rn}>0$ and $t_{ro}>0$ to the rental cost of regular-sized vehicles, with no change in the cost of small vehicles.²⁶ We choose the range from $t_{rn} = t_{ro} = 0.051$ to 0.510 (¥5,100 to ¥50,100 per year), in order to simulate the effects of an additional tax that ranges from one to ten times the existing annual fees on regular-sized vehicles (those over 2.00 liters). Figure 8 illustrates the results.

Because carbon emissions are related to vehicle size, this size tax in Figure 8 reduces CO₂ by larger percentages than it reduces local pollutants or *VKT*. None of these reductions is larger than 0.005 percent, however. As noted above, we found very

²⁴ Fullerton and West (2000) regress emission rate on engine size (in cubic inches of displacement) and find the coefficient is positive and significant at the ten percent level. When we use our U.S. sample with *all* cars, *EPM* is a U-shaped function of size. Four cylinder cars have less *EPM* than eight cylinder cars, but more *EPM* than six cylinder cars. The "small" car in Japan corresponds roughly to four cylinders in the US data, and regular cars correspond roughly to six cylinders, so small cars have higher emissions.

²⁵ For home-owned passenger cars, the annual fees are ¥29500 (1.0 liter or less), ¥34500 (1.001-1.5 liters), ¥39500 (1.501-2.0 liters), ¥45000 (2.001-2.5 liters), ¥51000 (2.501-3.0 liters), ¥58000 (3.001-3.5 liters), ¥66500 (3.501-4.0 liters), ¥76500 (4.001-4.5 liters), ¥88000 (4.501-6.0 liters), and ¥111000 (6.001 liters or more).

²⁶ Fullerton and West (2000) consider size as a continuous variable subject to tax.

small elasticities with respect to capital costs, both for car choices (Table 6) and for distance demand (Table 7). Thus, the simulated car ownership tax has only tiny effects on vehicle and distance choices. We find that this tax on engine size is not an effective policy tool for reducing emissions of any pollutants.

2.) A tax on the emissions rate (t_{EPK}). Since EPK_i is a characteristic of the car, this tax can be modeled also as a particular change in the annual cost of each vehicle. This tax may perform better than the size tax in reducing emissions, partly because emissions are more closely related to vehicle emission rates than to vehicle size. On the other hand, EPK_i is not as easily measured as engine size for the purposes of imposing the tax. To make t_{EPK} proportional to our estimated emission rates, we initially set $t_{rn} = 0.216$ (¥ 21,600/year), $t_{ro} = 0.402$, $t_{sn} = 0.288$ and $t_{so} = 0.549$. Then we simulate 10 to 100 percent increases in these tax rates. Figure 9 (a) shows the results. The initial set of taxes induces an almost 0.6 percent reduction of all variables (local emissions, CO₂, and VKT). Doubling those tax rates achieves 1.1 percent reductions. This kind of tax *could* lead to a percentage cut in emissions larger than the percentage cut in VKT demand, but only if it shifts households into cars with lower emission rates. These taxes affect capital cost, which has been shown to have only small effects on car choices. Figure 9(b) shows how this tax induces small changes in market shares.

3.) A tax related to the age of the vehicle (t_{age}). In our framework, t_{age} could be modeled as a tax on old cars or a subsidy to buying a new car. Age is much more observable than EPK_i , yet highly correlated with emissions, so this policy might be nearly as effective as t_{EPK} . A disadvantage may be that a tax or subsidy related to age does not provide any incentive for maintenance to reduce the vehicle's emissions rate, as would a tax on EPK .

In 2002, the Japanese government began implementing a Green Tax structure that adds 10 percent to the annual vehicle taxes already imposed on gasoline-operated vehicles that have been registered since 1991. Vehicles of eleven years of age or older continue to be subject to this yearly penalty in Japan. This policy is modeled here by setting $t_{rn} = t_{sn} = 0$ and $t_{ro} > 0$, $t_{so} > 0$. We start with additional taxes only on old cars that are ten percent of existing taxes ($t_{ro} = 0.051$ and $t_{so} = 0.0345$), and we test the sensitivity of results by raising those rates up to 100 percent of existing taxes.

Figure 10(a) shows that this age tax has very similar effects on all continuous variables (local emissions, CO₂, and VKT). With added taxes equal to 100 percent of existing taxes, these variables all fall by 0.35 percent. Compared to the tax on size, this tax on age raises the rental cost per vehicle by the same or less, and yet it induces more emission abatement and VKT reduction. The reason is that a large proportion of households own old cars and thus are affected by the tax. Figure 10(b) shows that this age tax discourages old cars that are small (*so*), but not necessarily larger old cars (*ro*). It does provide for slightly larger increases in the no-car share and new car shares.

C. The Marginal Cost of Abatement (MCA)

In order to compare the "cost-effectiveness" of different abatement technologies, many studies estimate production or cost functions and plot the marginal cost curve for using each technology to achieve more pollution abatement. Efficiency requires that these technologies be undertaken to the point where all have the same MCA. Then one can put all curves on the same diagram, draw a horizontal line at the allowed MCA, and show exactly how far to take each technology. Similar analysis for vehicles might show the MCA for adding a type of equipment or for reducing distance.

In this paper, we introduce a somewhat new view of cost-effectiveness, comparing policies instead of technologies. A policy such as the gasoline tax, for example, might induce several changes in technologies (in this case, changes in all four car choices *and* all distance choices). For each rate of tax, we calculate how the combined changes in technologies affect emissions. We can also calculate the cost to consumers, which in this case is a loss of consumer surplus rather than cost of equipment per se. Comparing each tax rate to a slightly higher tax rate, we take the added DWL over the additional abatement as the marginal social cost of abatement.

To calculate the cost to consumers, we use the indirect utility function for each car choice. For each household (i.e. prefecture), we calculate the utility level at the old equilibrium and at the new taxed equilibrium. We then iterate numerically to find the equivalent variation (EV), the yen amount that could be given to each household at the old prices that would allow them to attain the new utility level. This amount is negative for a loss, so the consumer cost of a tax is $-EV$. Government obtains some added revenue, ΔR , so the social cost or "deadweight loss" of the tax is $DWL = -EV - \Delta R$.

This DWL generally starts near zero and rises with the square of the tax rate, so one might expect the MCA to start near zero and to rise at an increasing rate.

For each tax instrument, we increment the tax rate and calculate the average household's change in local pollutants, the change in CO₂ emissions, and marginal social cost (added DWL). Thus we can show all MCA curves for local emissions in Figure 11, and all MCA curves for carbon emissions in Figure 12. The two diagrams are quite similar. All marginal cost curves are increasing, as expected. Perhaps surprisingly, the MCA are quite low for car taxes (t_{age} and t_{EPK}). Indeed, theory suggests that the tax on emissions (t_e) is the least cost way to reduce emissions. The explanation is that this theory must be modified in a second best model with other existing taxes. The existing gasoline tax in our model is 53.8yen/liter, which essentially doubles the price of gasoline. Thus, any additional gas tax starts with a high *marginal* DWL. In Figure 11, the marginal cost of raising this existing gas tax is ¥5,000 for the *first* additional gram of abatement per household.

Moreover, the cost of the existing gas tax is the consumer surplus lost from reduced driving, and that cost is exacerbated by any tax that further affect distance – such as the tax on distance (t_d) or on emissions (t_e or t_c). All those taxes start with MCA of about ¥5,000/gram and rise from there. Among those taxes, the tax on emissions *does* have the lowest MCA. In contrast, however, the car taxes (t_{age} and t_{EPK}) do not exacerbate the pre-existing cost of reduced driving distance. If these car taxes induce any switch toward low emission cars, then they can reduce emissions at very low initial marginal cost of abatement.

Given that the existing gas tax already achieves some abatement, mostly through *VKT* reduction, this analysis suggests that further abatement from the use of distance-reducing taxes is more costly than achieving some marginal abatement from induced changes in car choices. The option with the lowest cost is to tax each car at a rate proportional to its emission rate in grams per kilometer.

V. Conclusions and Future Research

This paper develops a model for simultaneous estimation of consumer behavior regarding discrete choice of vehicle and continuous choice of distance driven in Japan. We make unique use of prefectural average data on households, the 2000 Population

Census, and vehicle ownership information in Japan, all combined with fuel efficiency and emission rates estimated from U.S. vehicle testing data. We estimate the equations of this model simultaneously using general method of moments, and we find expected signs of effects on vehicle and driving choices from changes to income, the annual cost of each vehicle type, and the cost per kilometer of driving. Then we simulate different policy alternatives and show how they change driving distance and emissions.

Our model provides several opportunities for future research. First, it could be used to calculate the welfare-maximizing rate for all of these policy instruments simultaneously. This possibility provides a computational analog to the voluminous literature on “optimal tax rates”. Second, the standard errors from the estimation could be used to calculate the standard errors around the predicted outcomes (costs, emission levels, and optimal tax rates). Third, the model could be used to analyze distributional results, with households categorized on some meaningful basis (such as annual or lifetime incomes). The set of all household equivalent variations could be used to calculate changes in Gini coefficients or progressivity indices. The usual expectation is that most of these emission policies are regressive: gasoline and other driving expenses constitute a relatively large fraction of the spending of low-income families, and so any pollution policy that taxes gasoline or driving is likely to have disproportionate impact on low-income families. This is a major factor that has discouraged the use of incentive policies to deal with vehicle emissions problems.

In this case, however, the model could be used to analyze specific *subsidies* to reduce emissions. If those subsidies are accepted by households with low income, and if those households also have high emissions, then the subsidies might have relatively low cost of abatement *and* favorable distributional effects. This kind of result cannot be calculated by any model other than one incorporating all of the factors discussed above: heterogeneity among households in terms of incomes and other characteristics that affect discrete choice of vehicle and continuous choice of distance; estimation of parameters and standard errors; a model that can incorporate multiple kinds of tax and subsidy policies that affect the relative price of kilometers driven in each vehicle choice; technical information to calculate emissions from each car; and a simulation model that can calculate household welfare effects.

Table 1: Definitions and Summary Statistics

Variable Name	Variable Definition	Mean Value ^a
Famsize	Average number of people in a household	2.797 (0.018)
Education ^b	Fraction of residents with higher education	0.231 (0.005)
Metro	Fraction residing in densely inhabited districts	0.504 (0.016)
Child	Fraction of population less than 15 years old	0.147 (0.001)
Earners	Number of income earners per household	1.419 (0.012)
Two-earn	Dual-income fraction of households	0.346 (0.005)
Age	Average age of the head of a household	52.6 (0.133)
Own-home	Homeowners fraction of households	0.655 (0.006)
Y	Yearly total expenditure (in ¥ 100,000)	37.57 (0.275)
Gas Expenditure	Yearly expenditure on gasoline (in ¥ 100,000)	0.5139 (0.013)
Gasoline price	Gasoline price (in ¥ per liter)	101.09 (0.267)
N	Number of households in prefecture	1,001,335 (87,586)

(a) Standard errors in parenthesis.

(b) "Education" is the number of residents with more than high school education divided by the number of residents with at least 6 years of education not currently in school.

Table 2: Estimation of Fuel Efficiency and Emission Rate

	<i>Dependent Variable</i>	<i>Constant</i>	<i>Age</i>	<i>R²</i>	<i>Number of observations</i>
<u>Fuel Efficiency</u>					
Regular-size cars	ln(MPG)	3.093 (0.0293)	-0.0083 (0.0029)	0.083	96
Small-size cars	ln(MPG)	3.382 (0.0250)	-0.0128 (0.0021)	0.217	138
<u>Emission Rates</u>					
Regular-size cars	ln(EPM)	-1.2067 (0.1259)	0.1480 (0.0122)	0.609	96
Small-size cars	ln(EPM)	-0.8850 (0.1300)	0.1176 (0.0108)	0.465	138
<u>Carbon Dioxide (CO₂) Emission Rates</u>					
Regular-size cars	ln(CPM)	6.008 (0.0413)	-0.0006 (0.0122)	0.0006	48
Small-size cars	ln(CPM)	5.672 (0.0357)	0.00914 (0.0027)	0.144	69

Notes: Standard errors are reported in parenthesis. These regressions use U.S. data to estimate miles per gallon (MPG), emissions per mile (EPM), and carbon dioxide emissions per mile (CPM) for Japanese cars only. When applied to cars in Japan, these are converted to kilometers per liter (KPL), emissions per km (EPK), and carbon dioxide emissions per km (CPK).

Table 3: Summary Statistics of the Choice-specific Variables

Choices	<i>rn</i>	<i>ro</i>	<i>sn</i>	<i>so</i>	Means
Proportion choosing bundle <i>i</i>	0.042 (0.000)	0.210 (0.001)	0.081 (0.002)	0.453 (0.003)	0.1965
Fuel efficiency (KPL _{<i>i</i>})	9.294	8.975	12.348	11.703	10.580
Emission rate (EPK _{<i>i</i>})	0.216	0.402	0.288	0.549	0.364
CO ₂ emission rate (CPK _{<i>i</i>})	252.43	251.79	182.30	191.64	219.54
Market value (<i>k_i</i> in ¥100,000)	24.649	7.708	14.462	3.436	12.564
Gasoline cost (<i>p_i</i> in ¥/km)	10.88 (0.029)	11.26 (0.029)	8.19 (0.022)	8.64 (0.022)	9.74

Notes: Standard errors are reported in parenthesis. KPL is kilometers per liter. EPK is emissions per kilometer (km). CPK is carbon-dioxide per kilometer.

Table 4: Simultaneous Estimation of Discrete Choice and Continuous Demand

Variables	Parameters	t-statistic	P-value
Net income (β)	-0.0062	-3.034	[.002]
Gas cost per kilometer of choice one (α_{1rn})	-1.032	-42.62	[.000]
Gas cost per kilometer of choice two (α_{1ro})	-0.211	-65.78	[.000]
Gas cost per kilometer of choice three (α_{1sn})	-0.291	-37.78	[.000]
Gas cost per kilometer of choice four (α_{1so})	-0.064	-49.61	[.000]
Constant for choice one (α_{0rn})	5.178	11.04	[.000]
Constant for choice two (α_{0ro})	6.920	14.11	[.000]
Constant for choice three (α_{0sn})	5.455	11.43	[.000]
Constant for choice four (α_{0so})	2.831	5.830	[.000]
Constant for continuous choice (α_{00})	8.765	33.34	[.000]
Famsize	-0.102	-1.587	[.112]
Education	-0.716	-3.299	[.000]
Metro	-0.274	-3.716	[.000]
Child	3.383	4.343	[.000]
Earners	0.130	2.579	[.000]
Two-earn	-1.005	3.742	[.000]
Age	-0.014	-4.504	[.000]
Own-home	1.404	6.761	[.000]
Dummy for Tohoku	0.028	1.318	[.188]
Dummy for Kanto	-0.031	-1.348	[.178]
Dummy for Hokuriku	0.050	1.795	[.073]
Dummy for Chubu	0.030	1.187	[.235]
Dummy for Kinki	-0.110	-4.567	[.000]
Dummy for Chugoku	0.083	3.737	[.000]
Dummy for Shikoku	-0.034	-1.470	[.142]

Note: Total expenditures and capital cost are normalized in ¥100,000. Standard errors are computed from heteroscedastic-consistent covariance matrix.

Table 5: Estimated Own-Price and Cross-Price Elasticities of Each Choice with respect to gas cost (p_i)

Prices \ Choices	rn	ro	sn	so
p_{rn}	-1.389E-4	6.087E-6	6.087E-6	6.087E-6
p_{ro}	0.219	-0.825	0.219	0.219
p_{sn}	0.061	0.061	-0.694	0.061
p_{so}	2.249	2.249	2.249	-2.713

Note: Cell entry i, j (where i indexes the row and j indexes the column) gives the percentage change in probability of choosing car j for a one percent change in gas cost per kilometer of choice i .

Table 6: Estimated Own-Price and Cross-Price Elasticities of Each Choice with respect to capital cost (k_i) and total expenditure (y)

Capital cost \ Choices	rn	Ro	sn	so	0 (no car)
k_{rn}	-0.0301	0.0013	0.0013	0.0013	0.0013
k_{ro}	3.54E-4	-0.0013	3.54E-4	3.54E-4	3.54E-4
k_{sn}	0.0011	0.0011	-0.0127	0.0011	0.0011
k_{so}	0.0202	0.0202	0.0202	-0.0243	0.0202
<i>Total expenditure</i> (y)	-0.717	-0.876	-0.766	1.038	-0.909

Note: Cell entry i, j (where i indexes the row and j indexes the column) gives the percentage change in probability of choosing car j for a one percent change in capital cost of choice i .

Table 7: Short-Run Kilometer Elasticities

Elasticities of <i>VKT</i> with respect to:	Values
gas cost per kilometer of <i>choice rn</i> ($e_{p,rn}$)	-11.23
gas cost per kilometer of <i>choice ro</i> ($e_{p,ro}$)	-2.378
gas cost per kilometer of <i>choice sn</i> ($e_{p,sn}$)	-2.383
gas cost per kilometer of <i>choice so</i> ($e_{p,so}$)	-0.555
total expenditure (e_y)	0.233
capital cost of <i>choice rn</i> ($e_{k,rn}$)	-0.038
capital cost of <i>choice ro</i> ($e_{k,ro}$)	-0.012
capital cost of <i>choice sn</i> ($e_{k,sn}$)	-0.022
capital cost of <i>choice so</i> ($e_{k,so}$)	-0.005

Note: All the elasticities are evaluated at the mean values of the variables.

Table 8: Comparison of Tax Instruments

Δp(yen/km)	0	0.254	0.509	0.763	...	4.577	4.831	5.085
t_g (yen/liter)	0	2.690	5.380	8.070	...	48.420	51.110	53.800
t_e (yen/gram)	0	0.699	1.398	2.098	...	12.586	13.286	13.985
t_c (yen/gram)	0	0.001	0.002	0.003	...	0.021	0.022	0.023
t_d (yen/km)	0	0.254	0.509	0.763	...	4.577	4.831	5.085

Note: Taxes in a column induce the same amount of change in operation cost per-kilometer. Average price of gasoline in our data is 101.96 yen per liter.

Figure 1: Effects of Four Policies on Vehicle-Kilometers Traveled (VKT)

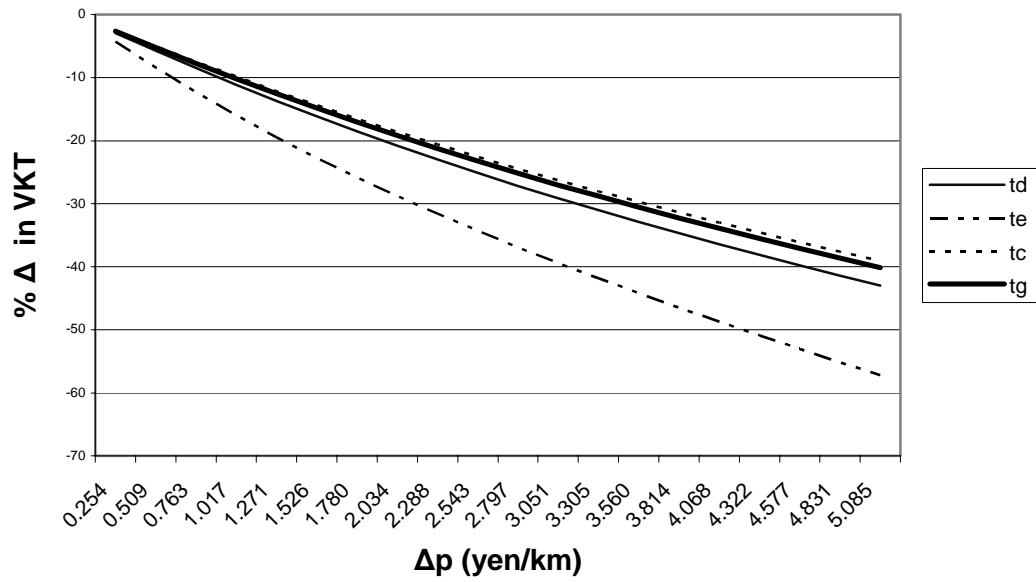


Figure 2: Effects of Four Policies on Local Emissions

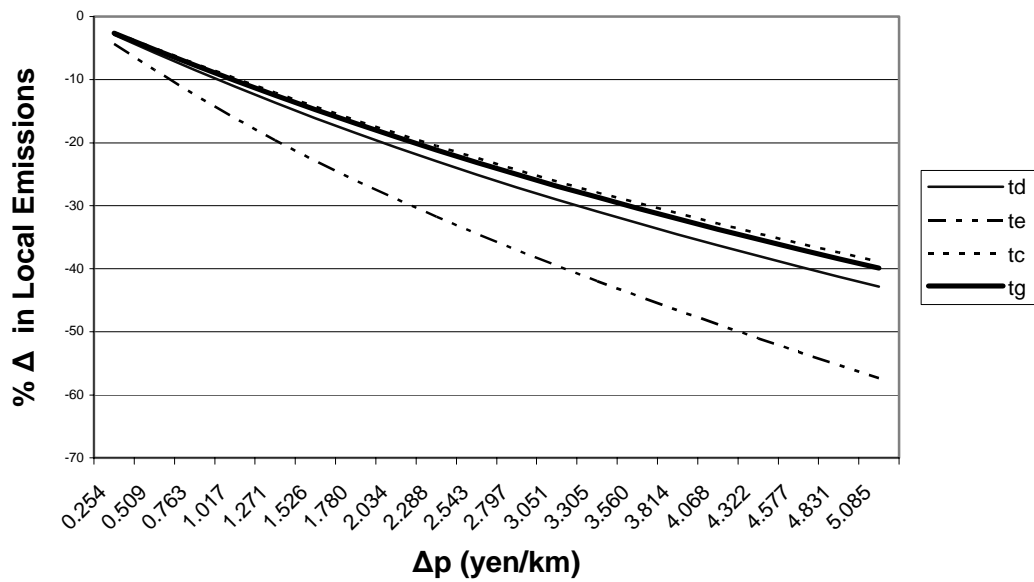


Figure 3: Effects of Four Policies on Carbon Emissions

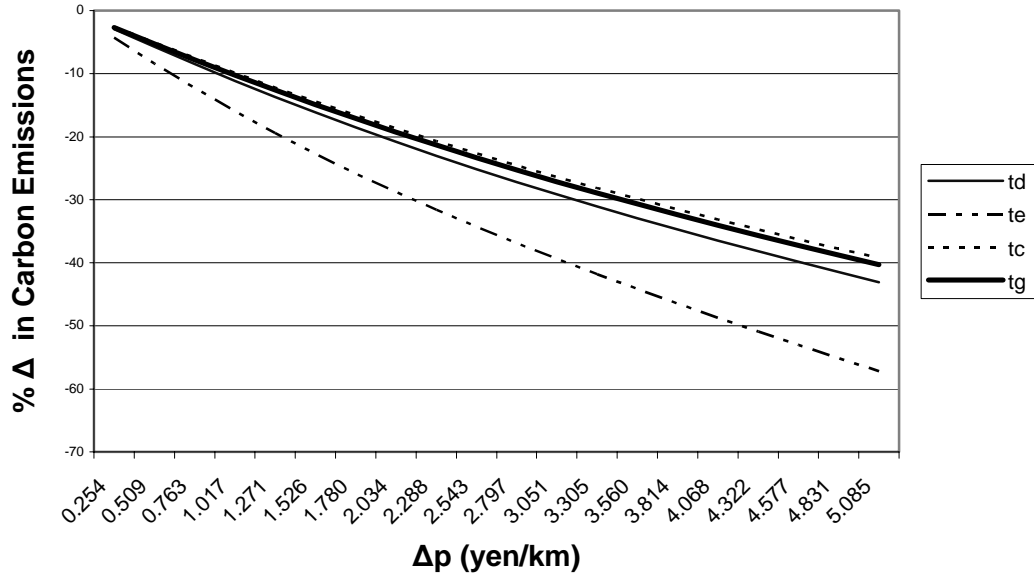


Figure 4: Effects of Emission Tax on Market Shares of Cars

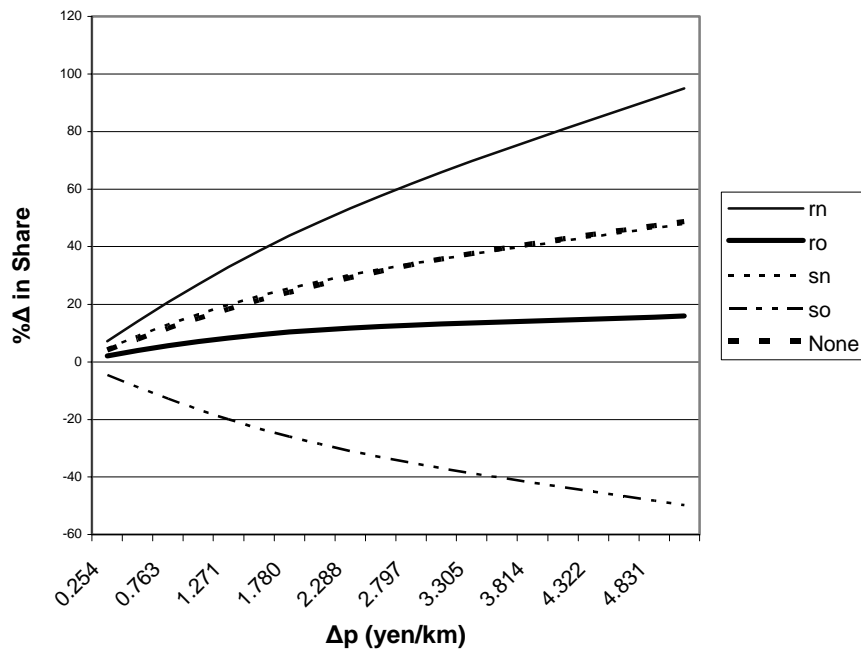


Figure 5: Effects of Carbon Tax on Market Shares of Cars

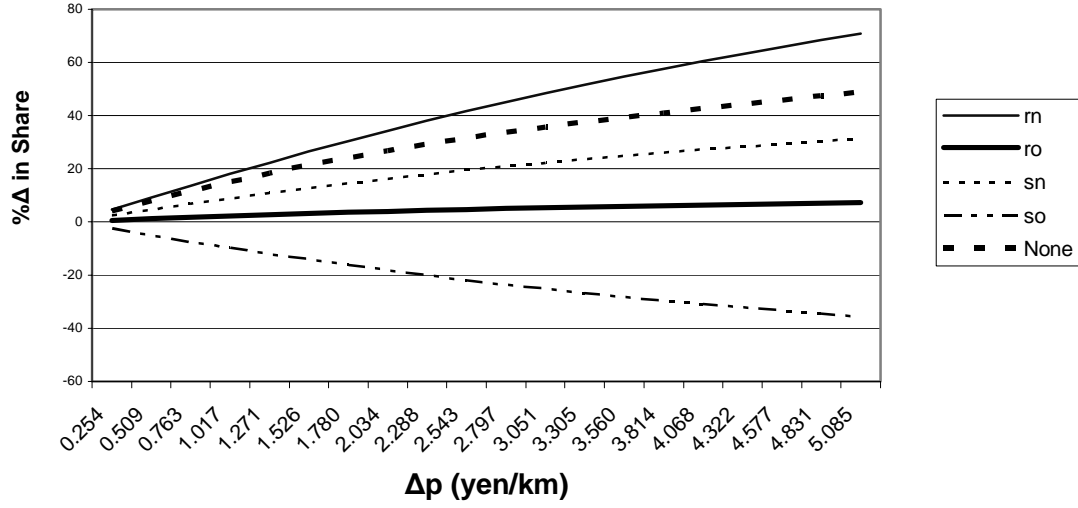


Figure 6: Effects of Gasoline Tax on Market Shares of Cars

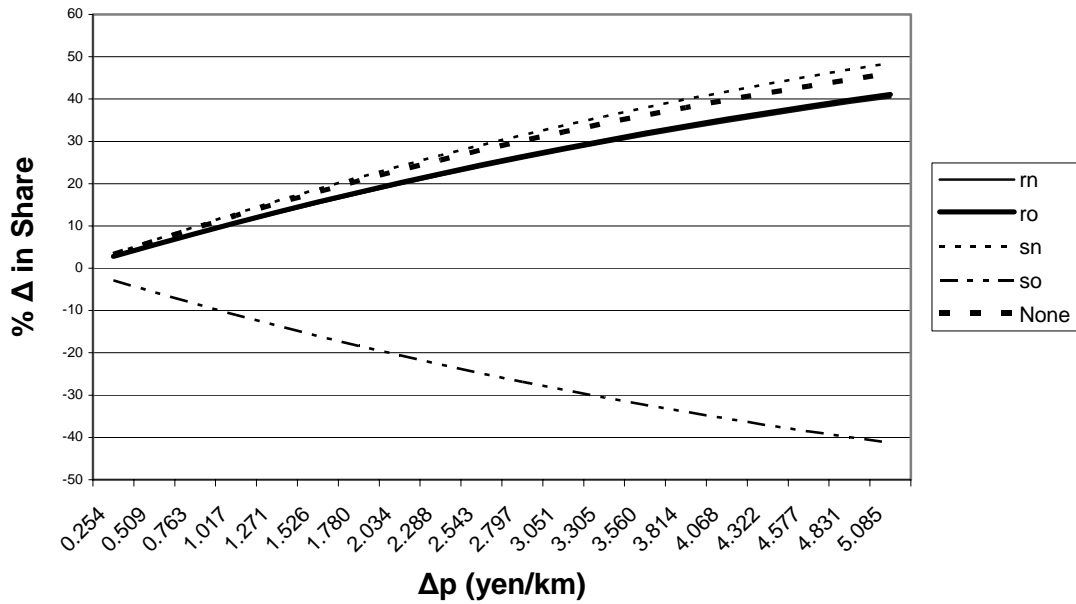


Figure 7: Effects of Distance Tax on Market Shares of Cars

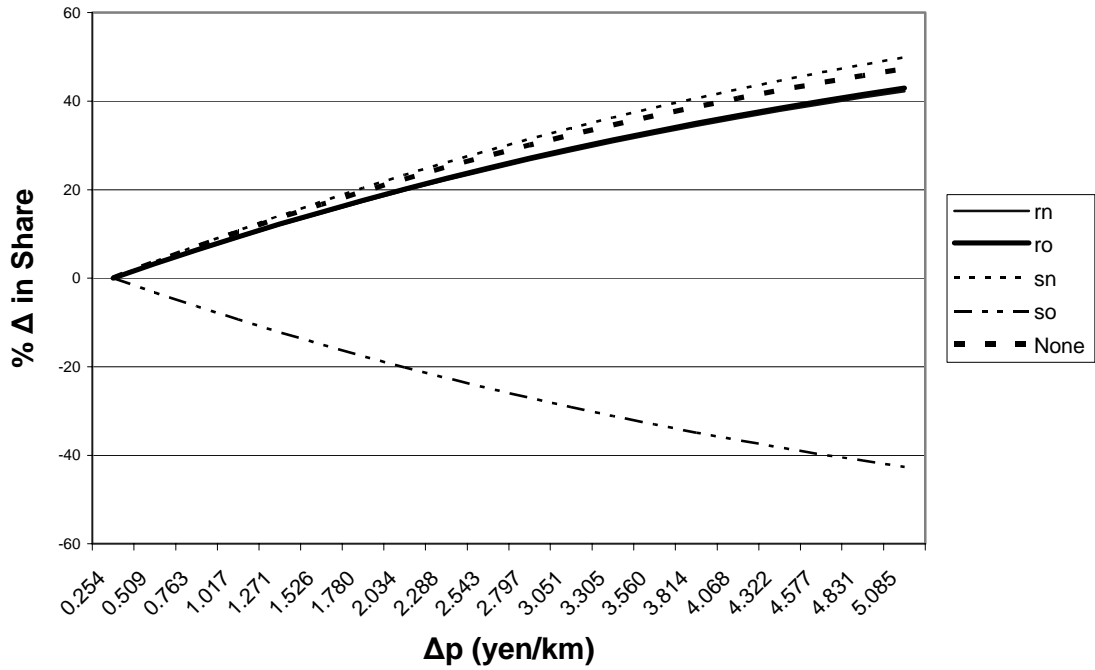


Figure 8: Effects of Size Tax on VKT, Carbon, and Local Emissions (LE)

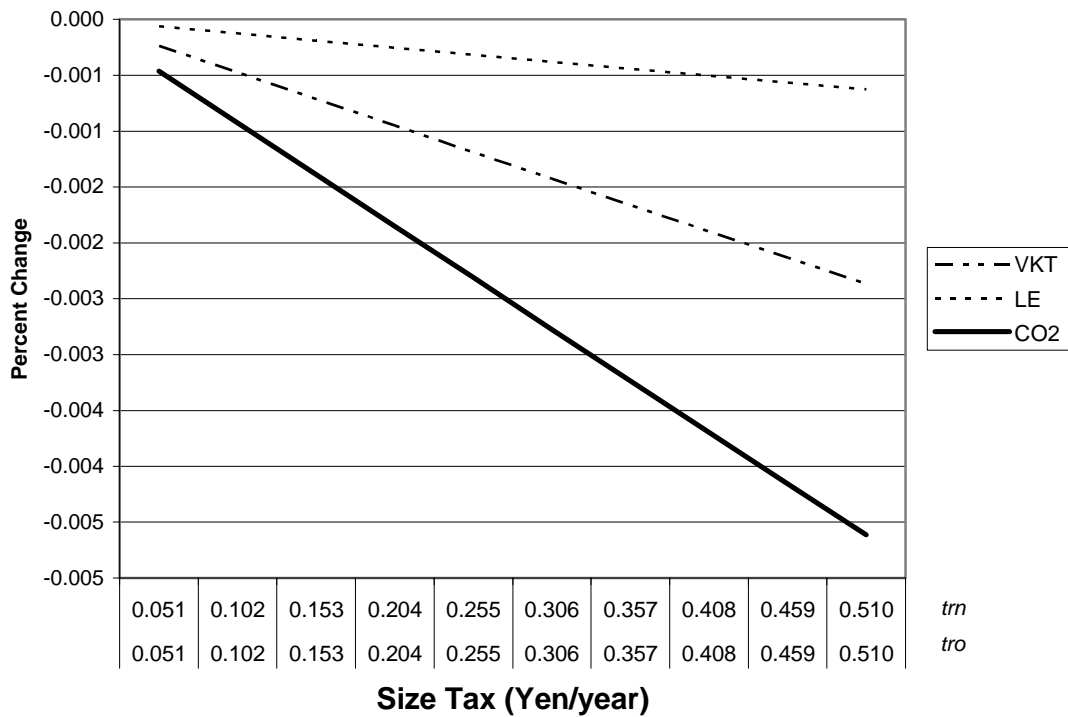


Figure 9 (a): Effects of an EPK-Proportional Tax

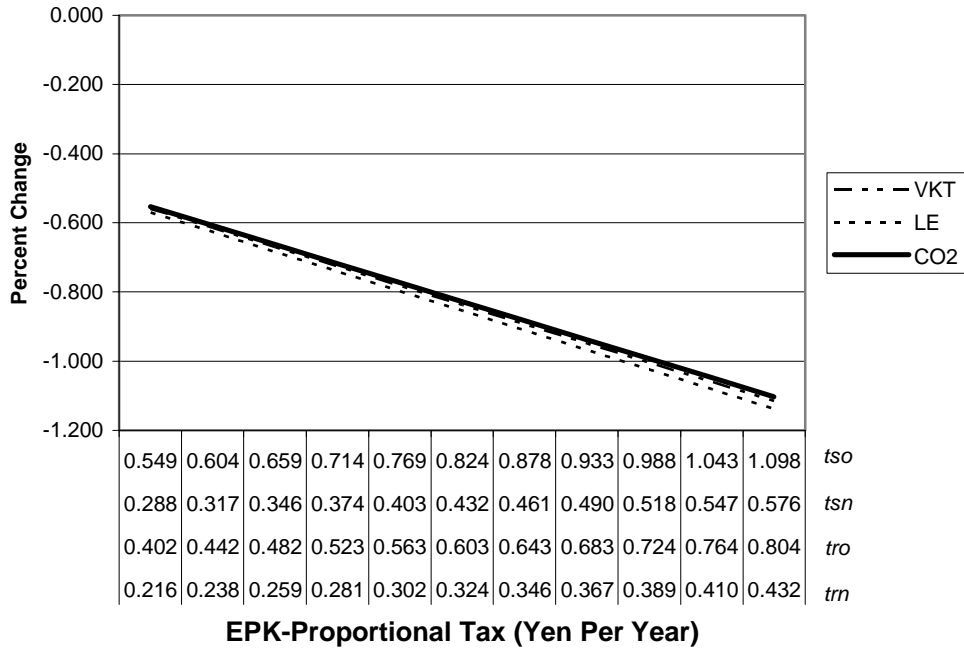


Figure 9 (b): Effects of an EPK Tax on Market Shares of Cars

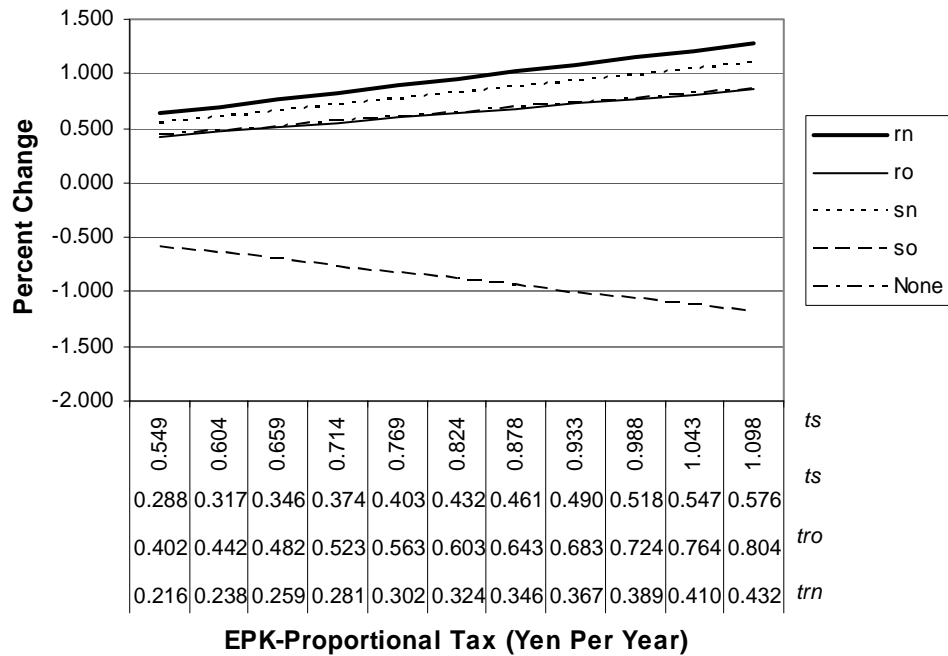


Figure 10 (a): Effects of a Tax on Old Cars

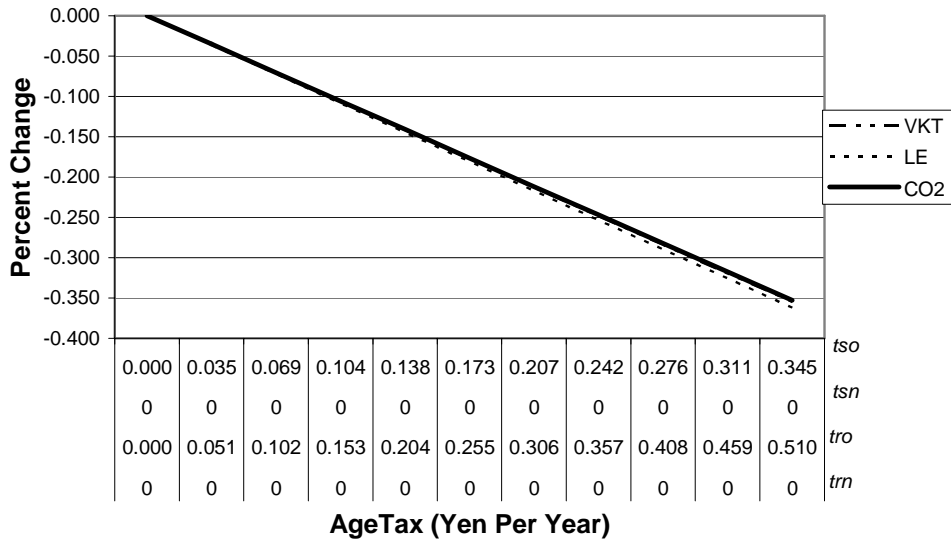


Figure 10 (b): Effects of a Tax on Old Cars on Market Shares of Cars

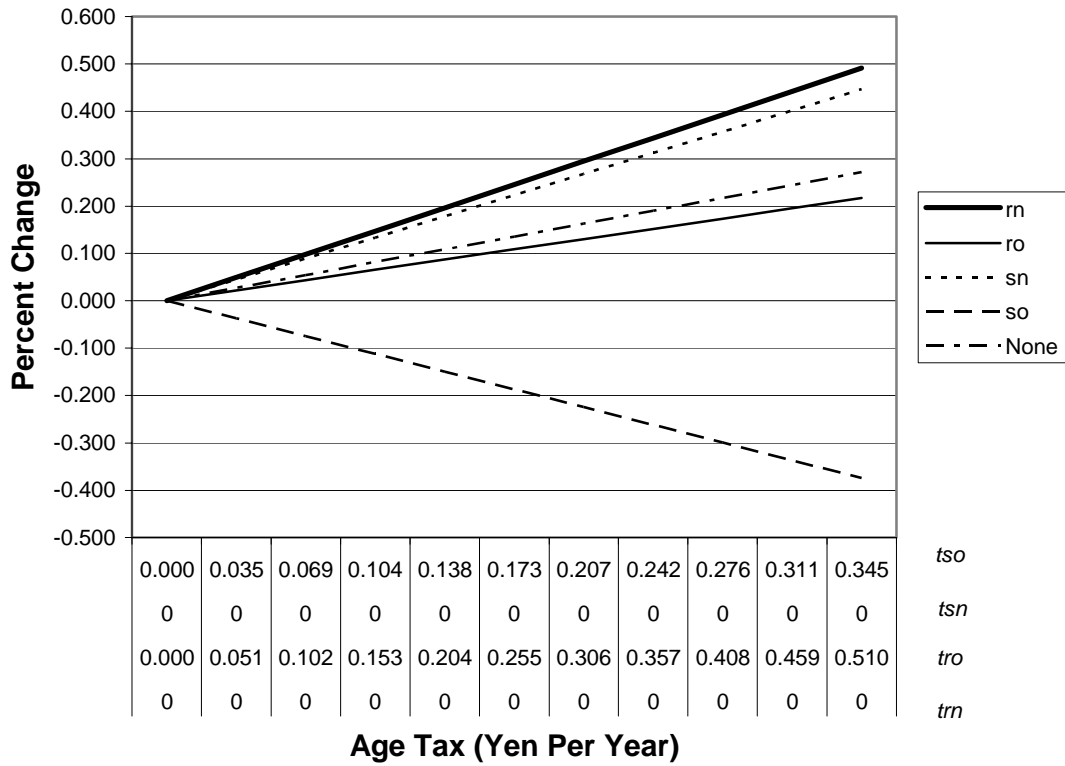


Figure 11: Marginal Cost of Abatement (MCA) for Local Emissions

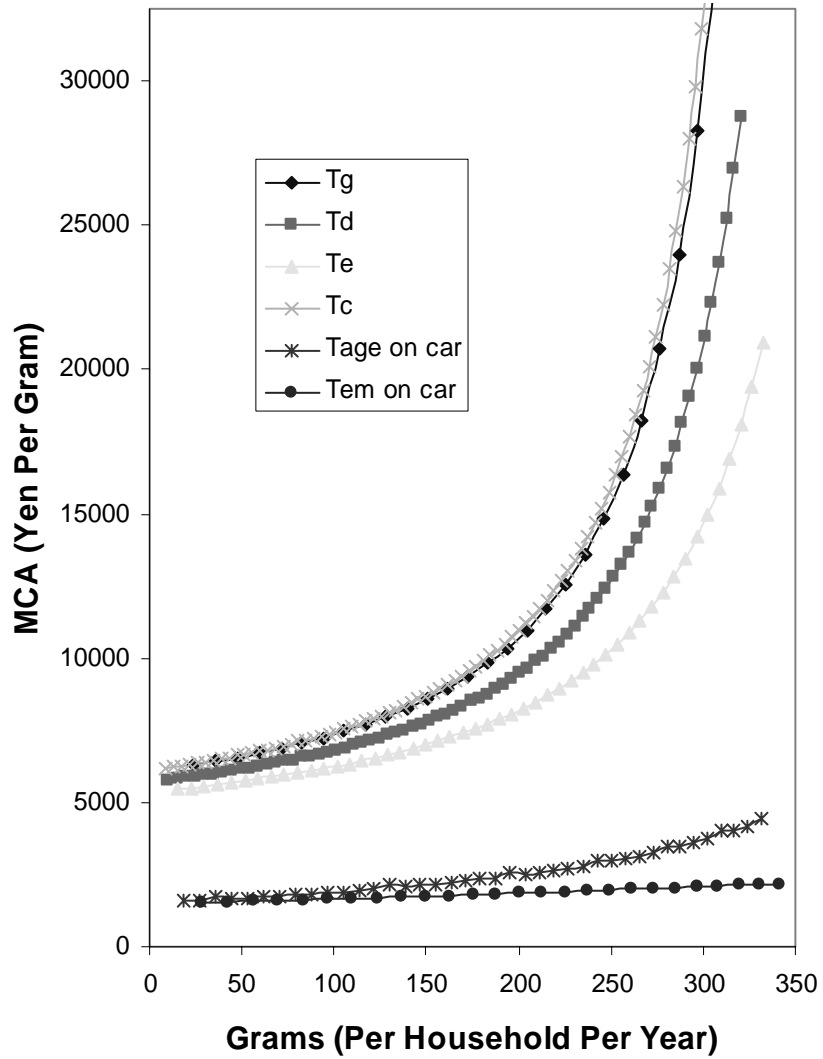
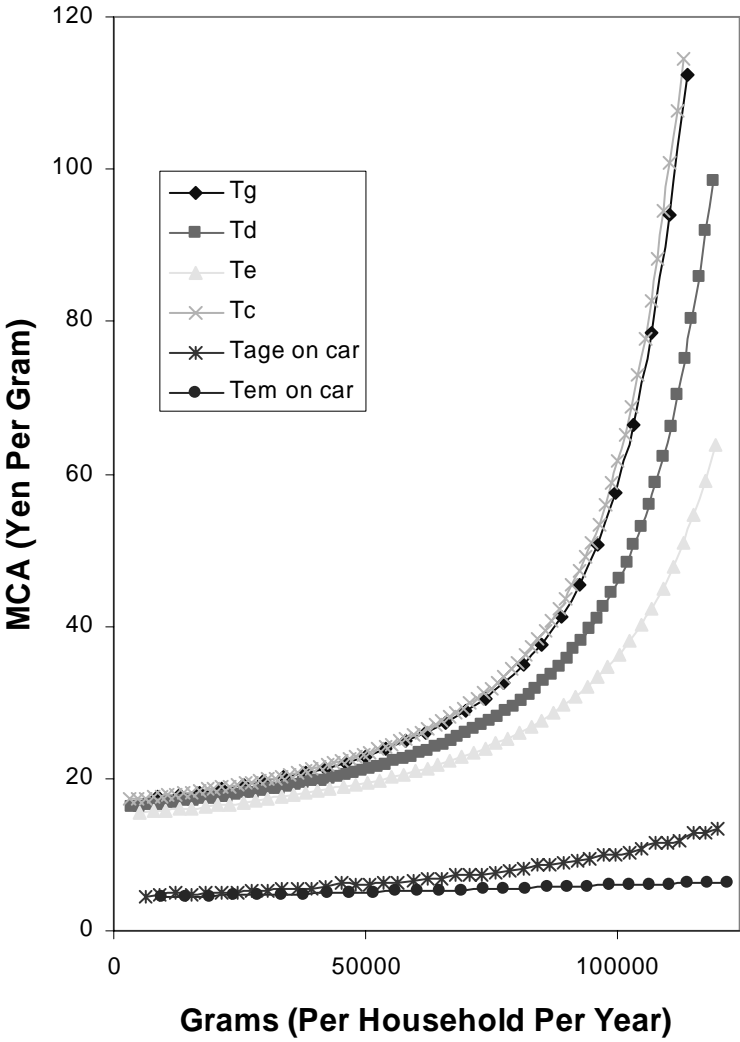


Figure 12: Marginal Cost of Abatement (MCA) for Carbon Emissions



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