Welfare Effects of Fuel Tax and Purchase Incentives for Low-Emission Vehicles[*]

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Abstract

A combination of a fuel tax and an incentive policy to promote low-emission vehicles has been adopted as a measure to reduce vehicle emissions worldwide. This paper examines the efficiency and distributional effects of these two policies. To do so, I estimate a model in which households simultaneously make decisions about car ownership and usage using household-level survey data and product-level aggregate data on the Japanese new car market. Counterfactual analyses indicate that the Japanese purchase incentives result in a rebound effect, offsetting approximately 7% of the CO_2 emission reduction achieved by the shift in the fleet composition toward low-emission vehicles. I also find that a fuel tax is less costly and less regressive than a purchase incentive that increases registration taxes for fuel-inefficient vehicles to achieve the same environmental benefits. This suggests that replacing registration taxes with fuel or carbon taxes could improve social welfare without increasing the tax burden on low-income households in Japan.

Keywords: Discrete-continuous choice, Fuel tax, Incentives, Rebound effect, Distributional impact, Tax incidence
JEL Codes: D12, H23, L62, Q53

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1 Introduction

A combination of a fuel tax and an incentive policy to promote low-emission vehicles has been adopted as a measure to reduce vehicle emissions worldwide. Fuel or carbon taxes are an efficient instrument to reduce emissions from car use by equalizing marginal abatement costs of emissions across households with divergent usage patterns. However, the taxes are generally considered regressive, making it politically challenging to raise them in the future. On the other hand, purchase incentives for low-emission vehicles aim to promote the sales shift toward them by taxing or subsidizing new car buyers depending on vehicle emissions rates. Purchase incentives have been accepted by many countries as an economic stimulus measure with an environmental objective, especially in response to the global financial crisis of 2007–2008 and the COVID-19 crisis (IHS Global Insight, 2010a,b). Recent years have seen a growing trend of expenditure on this policy in the global automobile market.

This paper examines the efficiency and equity of a fuel tax and a purchase incentive for low-emission vehicles. To do so, I rely on a model in which households simultaneously make two decisions about car ownership and use. This approach is crucial in assessing the two policies in terms of their efficiency and distributional equity. Fuel taxes impact not only the mileage choices made after purchasing a car, but also the car choices by changing the expected fuel costs associated with driving. Purchase incentives directly influence car choices by encouraging households to buy fuel-efficient vehicles, and indirectly affect mileage choices by changing the attributes of the purchased vehicles. Therefore, the incidence of taxes and incentives on households, as well as their effects on social welfare, depend on the household decisions regarding car ownership and usage.

In addition, the environmental implications largely depend on the interaction between the two decisions. Fuel taxes and purchase incentives have an emission reduction effect by shifting the fleet composition toward fuel-efficient vehicles. However, these policies may also result in a rebound effect that partially offsets their emission-reducing benefits. The rebound effect refers to the increased driving demand due to the improved fuel economy of purchased vehicles followed by a downward shift in the marginal cost of driving. Therefore, policies that encourage households to purchase fuel-efficient vehicles may not always result in the intended reduction of fuel consumption (Anderson and Sallee, 2016). In particular, compared with fuel taxes, purchase incentives are likely to result in a significant increase in emissions from car use due to the rebound effect because they fail to control driving demand after purchase.

In this context, this paper seeks to answer the following questions: What are the consequences of a fuel tax and a purchase incentive for low-emission vehicles on social welfare? How much does the rebound effect induced by each policy contribute to the increase in emissions? How regressive is a fuel tax compared to a purchase incentive?

I study a fuel tax and a purchase incentive implemented in Japan. The Japanese schemes provide interesting cases for the purpose of this study for several reasons. First, the purchase incentive has long contributed the promotion of low-emission vehicles in Japan since its expansion as part of the Green New Deal in 2009,. In fact, since 2009, new hybrid vehicle registrations have increased significantly, from 74,000 units in 2002 to 4.68 million units in 2015. The purchase incentive has been a centerpiece of car greening policy in Japan and has continued to the present. In addition, the purchase incentives have experienced several changes in coverage and the incentives, leading to rich price variations across vehicles and over time. The multidimensional price variations that are exogenous for households and automobile manufacturers play a key role in identifying model parameters. Second, the Japanese purchase incentive may lead to inequality among households with different incomes. Purchase incentives are known to favor high-income households who purchase fuel-efficient vehicles conditional on other vehicle attributes. Furthermore, the Japanese purchase incentive is an attribute-based regulation (Ito and Sallee, 2018). The attribute-based regulation determines incentives based on the secondary attributes such as weight and displacement, as well as the primary attribute of fuel economy. Therefore, the attribute-based feature may offer incentives that are disproportionate to the environmental benefits for high-income households, further exacerbating income inequality. Third, a carbon tax was introduced in Japan in 2012 on the top of the existing fuel taxes. The tax levied on fuel in Japan is at a high level compared to European countries.[1]

To examine the welfare effects of the two policies, I primarily use two different-level data sets. The first data set comes from a household survey conducted in 2013 to households in Japan who had purchased passenger vehicles within the past five years, including information on car ownership and utilization as well as demographics for each household. The second data set comes from aggregate data on the Japanese new car market between 2006 and 2013, containing information at the base model level. There are several advantages to using both household survey and aggregate market data. First, supplementing the household survey with the aggregate market data helps construct choice sets in each market that households surveyed face. Previous literature has considered household decisions about car ownership and usage to study regulations in the automobile market (e.g., Goldberg, 1998; West, 2004; Bento et al., 2009). These previous papers use large-scale surveys that contain individual-level detailed information on the choice and usage of cars and allow for the construction of a list of all cars sold in each market from a list of cars purchased by households surveyed. However, such micro data is not available in many countries. To overcome this issue, I combine the micro and macro-level data sets. Second, adding household-level information in micro data to product-level aggregate data plays a critical role in identifying household-specific parameters in a model.

I begin by developing a model that describes the behaviors of households and firms in the automobile market. On the demand side, I model the household decision makings as a two-stage problem. Specifically, I describe the car and mileage choices with the discrete-continuous choice

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[1] In Japan, while the carbon tax rate is still low level, gasoline and diesel have long been subject to fuel taxes with high tax rates, with the gasoline tax accounting for approximately one-third of the gasoline price.

(DCC) model following Bento et al. (2009). Using the DCC model allows me to drop the restrictive assumption made in most previous studies that estimate the demand for cars that the demand for driving is completely inelastic with respect to operating costs; I thus measure the policy effects without making any assumptions concerning the elasticity of driving demand. In addition, using the DCC model and the combined two data sets enables me to jointly estimate the demands for cars and use. I expect the joint estimation to produce efficient estimates of parameters in the two demand functions compered with separate estimation. On the supply side, following Berry et al. (1995) and subsequent studies, I consider the pricing strategies of car manufacturers in an oligopolistic market where differentiated, multiproduct firms determine their prices based on those of rival firms. In estimation, I account for the car price endogeneity associated with demand estimation, leveraging aggregate market data in the analysis. I then estimate the parameters of the DCC model via a maximum likelihood estimation with market share constraint while addressing the endogeneity problem (e.g., Goolsbee and Petrin, 2004; Train and Winston, 2007; Goeree, 2008; Benetton, 2021).

Before the structural estimation, I present a preliminary evidence on the rebound effect. The result from a simple OLS regression of mileage on the operating cost suggests a large interregional difference in the rebound effect over the sample period in Japan, reflecting diverse responses of driving distance to the change in the driving cost across regions.[2] The finding motivates me to account for the heterogeneity in the rebound effects across households in a structural model. Specifically, my model accommodates several random coefficients to capture the household-specific heterogeneity, which microdata used in this study also help to identify.

I make two findings associated with the rebound effect. First, the result from the structural estimation indicates that the rebound effect averages 0.09%, with spreading over an interquartile range of 0.07–0.11%. This means that a 1% decrease in the cost of driving per kilometer increases driving demand by 0.09% on average. Second, it turns out that the OLS estimate of the rebound effect is considerably biased upward, compared to the above estimate from the structural estimation. This fact demonstrates that the lack of the consideration of households' endogenous car choice causes a selection bias in estimates of parameters in the demand function for car driving (Dubin and McFadden, 1984).

Based on the estimated parameters, I conduct counterfactual analyses to assess welfare effects of a purchase incentive and a fuel tax with four different measures of surplus: consumer surplus, producer surplus, tax revenues, and environmental externalities. I find that while the Japanese purchase incentive significantly increases social welfare by stimulating demand for automobiles and mitigating the distortion in the oligopolistic market, it exacerbates environmental externalities. The augmentation of the negative externality is partially attributable to the rebound effect as

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[2] This finding is consistent with existing literature that finds a significant disparity in the magnitude of the rebound effect across regions even within a given country due to the difference in car usage patterns between urban and rural areas (e.g., Gillingham, 2014).

well as an anticipated increase in the number of cars owned by households due to the stimulated demand. A decomposition analysis quantifies the contribution of the rebound effect to the increase in CO_2 emissions from car use, revealing that the rebound effect induced by the purchase incentive cancels out approximately 7% of the emissions reduction that would have been attained by the improvement in fuel economy. The result suggests that ignoring the individuals' behavioral change after the introduction of energy efficiency programs such as purchase incentives would significantly overestimate the emissions reduction effect of the policy even in the short run. Furthermore, the simulation shows that reforming the current purchase incentive scheme to change the attribute-based policy design to an emissions-based one has consumer welfare gains and mitigates inequality across households with different incomes while holding the environmental externality constant.

In addition, the counterfactuals demonstrate superiority of a fuel tax in terms of the cost-effectiveness and the distributional equity against an annual registration tax proportional to CO_2 emissions, an alternative purchase incentive considered in the simulation analysis. To evaluate real tax burdens on households, I value shadow costs of the current fuel tax in Japan and an externality-equivalent registration tax by measuring the losses of consumer welfare incurred due to these taxes. The estimated shadow costs suggest that the fuel tax is 1.7 times less costly than the registration tax to reduce environmental externalities by the same amount. Moreover, comparing the distributions of the tax burdens across income groups indicates that the taxes are both regressive and the degree of the regressivity of the fuel tax is more moderate than that of the registration tax.

This paper builds on several literature studying automobile tax and greening policies. I provide the first evaluation of the effects of the Japanese purchase incentive, which is the centerpiece of the automobile greening policy in Japan, on car purchase and usage behaviors on the demand side. Existing studies have demonstrated the effect of the purchase incentive on the market equilibrium and explored its optimal policy design by modeling car purchase decision by households (e.g., Wakamori, 2015; Kitano, 2016, 2022; Konishi and Zhao, 2017; Kaneko and Toyama, 2023). I contribute to the literature by investigating the effect on households' car usage decision as well.[3] Using a model that consistently describes car purchase and usage behaviors by households enables me to capture the changes in social welfare and emissions from car use after the policy introduction in more comprehensive way.

I also compare a purchase incentive and a fuel tax from the aspect of distributional equity. Empirical literature has not found consensus about how regressive fuel taxes are in comparison with other policy instruments. Previous studies have examined the distributional impacts of automobile-related taxes, such as a registration tax and a fuel tax, and environmental regulations, such as

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[3] There are existing papers that have examined the welfare effect of purchase incentives in different countries, such as France (e.g., D'Haultfœuille et al., 2014; Durrmeyer, 2022), Germany (e.g., Adamou et al., 2014), and Sweden (e.g., Huse and Lucinda, 2014). However, my work is the first to study a purchase incentive by using a model with households' car purchase and usage decisions and a data set that contains individual information on the two decision makings.

corporate average fuel economy standards and exhaust emission standards (e.g., West, 2004; Bento et al., 2009; Jacobsen, 2013; Xiao and Ju, 2014; Davis and Knittel, 2019; Levinson, 2019; Durrmeyer, 2022; Gillingham et al., 2022; Jacobsen et al., 2023). I contribute to the literature by comparing the regressivity of a fuel tax with that of an emission-based registration tax based on estimated shadow costs incurred at the stages of car ownership and utilization.

The remainder of this paper is organized as follows. Section 2 describes the data sets and institutional background of the Japanese purchase incentive and presents evidence suggesting a rebound effect during the sample period. Sections 3 and 4 outline the model and the estimation strategy, and Section 5 discusses the estimation results. Section 6 presents the results of counterfactual analysis, and Section 7 concludes the paper.

2 Data and Institutional Background

This section describes the data sets used in the analysis and the institutional background of the purchase incentive scheme in Japan. In particular, I highlight exogenous variation in vehicle prices generated by several system changes of the Japanese purchase incentive that is helpful for the identification of model parameters. I then present suggestive evidence for the existence of a rebound effect in Japan during the sample period.

2.1 Data

The data used for the analysis stem mainly from two data sets. The first data set comes from a household survey that includes information on household choices of car and use. This survey was conducted online in November 2013 by the Nippon Research Center (NRC) and randomly selected households nationwide who had purchased passenger cars in the past five years. Specifically, the survey has 548 observations with information on the model purchased, purchase year, total travel distance for each vehicle, and household demographics such as income, age of the household head, and the residential area address.

The second data set is a market-level aggregate data set for the period from 2006 to 2013. The market-level data supplement the survey data. Indeed, the market aggregate data help to construct the choice set facing individuals in the household survey. The aggregate data set provides panel data on sales and prices for vehicles sold in Japan. I obtain data on sales volumes of automobiles made by Japanese manufacturers from the Annual Report on New Motor Vehicle Registrations (*shinsha-touroku-daisuu-nennpou* in Japanese) published by the Japan Automobile Dealers Association and from statistics on mini-vehicles released by the Japan Mini Vehicles Association. I also collect information on the sales volumes of imported vehicles from statistics released by the Japan Automobile Importers Association (JAIA). The statistics include sales data on the top 20

Table 1: Summary Statistics

	Unit	Mean	Std. Dev.	1st Q.	3rd Q.
Panel A. Household survey ($N = 548$)					
Annual vehicle kilometers traveled (VKT)	10,000km	0.55	0.33	0.30	0.75
Household income	million JPY	7.56	4.23	4.35	9.64
Family size	person	2.92	1.13	2.00	4.00
Age of household head	age	54.62	12.59	45.00	64.00
Urban dummy	binary	0.47	0.50	0.00	1.00
Panel B. Aggregate market data ($N = 1,302$)					
Sales	1,000	24.70	40.05	3.11	28.31
Price	million JPY	2.68	1.90	1.50	3.08
Rental price	million JPY	0.58	0.37	0.36	0.65
Automobile-related taxes	million JPY	0.19	0.11	0.13	0.23
Cost of driving per kilometer	100 JPY/km	0.11	0.04	0.08	0.13
Horsepower per weight	ps/kg	0.10	0.03	0.08	0.11
Size	10 meters	0.75	0.07	0.69	0.81
Kei-car dummy	binary	0.20	0.40	0.00	0.00
Transmission dummy (AT/CVT)	binary	0.98	0.13	1.00	1.00

Note: This table summarizes descriptive statistics for the household survey and aggregate market data. The 1st Q. and 3rd Q. stand for the first and third quantiles. In Panel A, the annual VKT is calculated by the total travel distance divided by years of use, and the urban dummy indicates whether a household resides in ordinance-designated cities in Japan. In Panel B, the automobile-related taxes represent the lump-sum tax amount paid by new car purchasers at the time of purchase in the absence of the purchase incentive.

best-selling imported vehicles sold in Japan for each year.[4] In addition, I obtain information on the car attributes, including price, curb weight, size, and fuel economy, on the Carview! website. Consequently, the market aggregate data set contains 1,302 observations over eight years for each base model, with nine Japanese and seven overseas car manufacturers. I match the market-level data to micro data in the household survey using the model name common to both data sets.

In addition, I supplement the two main data sets with several data sources. First, I make use of the Comprehensive Survey of Living Conditions (CSLC) in 2013 administrated by the Ministry of Health, Labor and Welfare to construct the population density for household demographics. Second, I collect data on retail gasoline and diesel prices released by the Oil Information Center of the Institute of Energy Economics, Japan. I also exploit the 2015-base consumer price index released by the Statistics Bureau of Japan to deflate household income, car prices, and fuel prices.

Panel A of Table 1 presents the summary statistics for the household survey. The annual vehicle kilometers traveled (VKT) for each vehicle owned by surveyed households is approximately 5,480km

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[4] In Japan, imported vehicle sales constitute a small portion of total new vehicle sales. Indeed, JAIA (2016) reports that the share of imported vehicles in total new vehicle sales in 2013 was approximately 6.5%.

on average, which takes a value close to the national average of distance traveled.[5] Note that the average household income shown in the table is slightly higher than the national average since the NRC's survey only targets households who have purchased cars.[6] As for the other household demographics such as family size, age of the household head, and the urban dummy, I find that they have distributions close to the population.

Panel B reports the descriptive statistics of market aggregate data. The rental price represents the annual cost of vehicle ownership, which is calculated as the sum of depreciation, repayment amount of car loan interest, and annualized automobile taxes in each year.[7] I find that automobile-related taxes shown in the table amount to approximately 8% of the purchase price on average in the absence of the purchase incentive. Appendix A.1.1 provides detail explanation on automobile-related taxes that are composed of the acquisition tax, the tonnage tax, and the automobile tax during the sample period. In addition, the cost of driving per kilometer is defined as the fuel price (JPY/L) divided by the fuel economy (km/L), and the vehicle size is measured as the sum of the length, width, and height of the vehicle. Finally, the transmission dummy (AT/CVT) is a dummy variable indicating vehicles with an automatic transmission (AT) or a continuously variable transmission (CVT).

2.2 Japanese Purchase Incentive

I briefly describe the purchase incentive scheme in Japan. This section mainly aims to show how various system changes in the purchase incentive created variations in the vehicle prices consumers faced. The details of the purchase incentive are provided in Appendix A.1. The Japanese purchase incentive is essentially a rebate program, consisting of (i) the tax incentives and (ii) the subsidy program for fuel-efficient vehicles.[8] During the sample period 2006–2013, each of the tax incentive measures and the subsidy program experienced three and one system changes, respectively. Especially in the 2009 system reform, the Japanese government vastly expanded the coverage of vehicles

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[5] The Japan Automobile Manufacturers Association (JAMA) conducts a nationwide survey for households nationwide every two years and reports an average monthly VKT of 380km for 2013, which indicates a rough estimate of the annual VKT comes to 4,560km (JAMA, 2013).

[6] Indeed, the household income in my sample is 7.56 million JPY on average, while the population average reported in the CSLC for 2013 is 5.28 million JPY.

[7] The depreciation is calculated based on the legal durable years by type of vehicle. The National Tax Agency of Japan stipulates that the legal durable years are six years for ordinary passenger vehicles and four years for mini-vehicles (Kei-cars). Repayment amounts of car loan interest are calculated by the purchase price times the annual interest rate of 3%, which is roughly the average interest rate of car loans in Japan. The purchase price here includes the excise tax-inclusive price, an acquisition tax, and a subsidy amount in the presence of the purchase incentive. Finally, annualized automobile taxes consist of the total amounts of a motor vehicle tonnage tax and an automobile tax that car owners are obligated to pay every year.

[8] In addition to these programs, there was a cash-for-clunkers program for replacing gasoline vehicles registered for more than 13 years with fuel-efficient vehicles between 2009 and 2010. See Kitano (2022, 2023) for details of the cash-for-clunkers program.

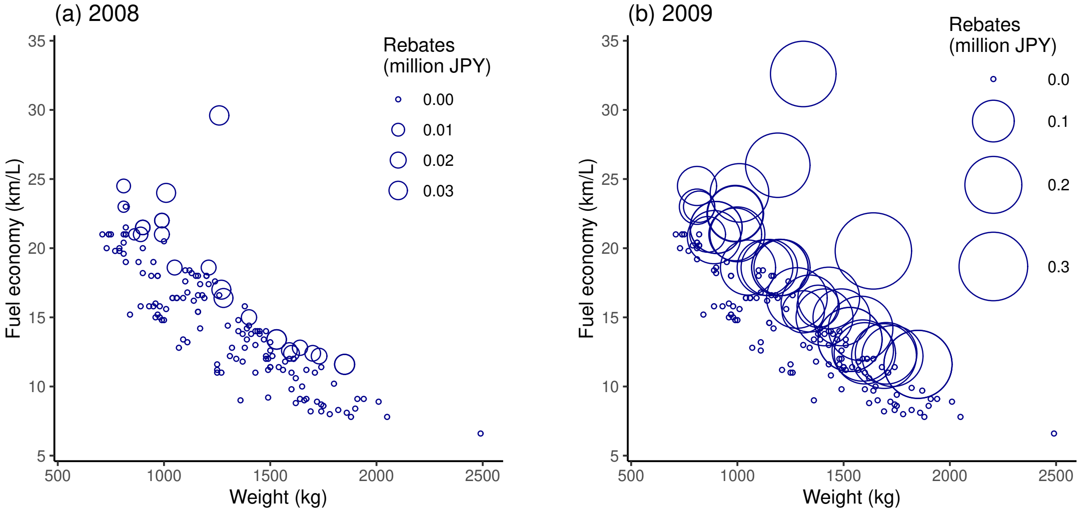

Figure 1: Variation in Rebate Amounts

Note: The bubble plots illustrate the rebate amounts provided by the purchase incentive for vehicles sold in 2008 (left figure) and 2009 (right figure). The rebate amounts for each vehicle are calculated as the sum of the tax cut and subsidy amounts.

targeted for the purchase incentive and increased the amounts of rebate to tackle the recession due to the financial crisis.

Figure 1 displays rebate amounts which are the sum of the tax cut and subsidy amounts applied for each car. From the two panels in Figure 1, I confirm that the 2009 system reform substantially altered the rebate amounts. Indeed, while vehicles sold in 2008 received at most 0.03 million JPY, some vehicles sold in 2009 received more than 0.3 million JPY. In addition, I observe over the sample period 2006–2013 that the rebates have rich time-series variations as well as cross-vehicle variations, ranging from 0 JPY to nearly 0.5 million JPY within a given vehicle. The multidimensional exogenous fluctuations in vehicle prices that consumers face are crucial for the identification of model parameters. I describe how the price variations are used to construct instrumental variables in later sections.

Furthermore, Figure 1 shows that the rebate amounts depend not only on the vehicle fuel economy but also on the vehicle weight, which indicates that the Japanese purchase incentive is an attribute-based regulation (Ito and Sallee, 2018). Basically, as summarized in Appendix Tables A.2 and A.3, the tax cut and subsidy amounts are determined by the achievement rate of the fuel economy standards target values that are set by vehicle weights. Figure 1 indeed shows that many heavy vehicles with relatively poor fuel economy receive greater rebates than hybrid vehicles with a fuel economy of almost 35 km/L. This fact suggests that under the Japanese purchase incentive fuel-efficient vehicles do not necessarily enjoy a higher benefit than less fuel-efficient vehicles.

Finally, I describe how the implementation periods of the purchase incentive are defined in my empirical analysis. Each of the tax incentive measures and the subsidy program have the following implementation periods: 2006, 2007–2008, April 2009–April 2012, and May 2012–2013 for the tax incentive measures, and April 2009–September 2010 and January 2012–September 2012 for the subsidy program.[9,10] Since the data available in this study are annual data, I divide the implementation periods of the tax incentives and subsidy programs after 2009 into 2009–2011 and 2012–2013. As discussed in later sections, even with such a division, the empirical results are found to be consistent with external data. This indicates that summarizing the monthly regulatory effects into annual effects does not have a significant impact on the analysis.

2.3 Suggestive Evidence

Before constructing a structural model, I show suggestive evidence of the presence of a rebound effect by simple regression analysis. The results in this section suggest that there might be interregional heterogeneity in the rebound effect during the sample period in Japan.

Using data in the household survey and aggregate data set, I estimate the following equation by OLS:

$$\log M_{ijt} = x'_{jt}\beta + h'_i\gamma - \rho \log p^M_{jt} + \varepsilon_{ijt} \tag{2.1}$$

In the equation, the dependent variable M_{ijt} is the annual distance traveled of car j purchased by household i in year t. On the right-hand side, x_{jt} and h_i are vectors of the vehicle and household characteristics, respectively, and p^M_{jt} represents the per-kilometer cost of driving. The above equation includes an idiosyncratic error term ε_{ijt}. The parameter of interest here is ρ, the coefficient of p^M_{jt}. Defining the rebound effect by the elasticity of driving demand M_{ijt} with respect to the cost of driving p^M_{jt}, the parameter ρ corresponds to the rebound effect. To verify the existence and interregional disparity of the effect, I add the interaction between $\log p^M_{jt}$ and population density in the area of household residence to (2.1).[11]

The estimation results are summarized in Table 2. The estimates of parameter ρ do not vary across specifications (2) and (3) in Table 2, and all are statistically significant. Using the results of Model 3, the national average of the rebound effect is found to be 0.24. This suggests that the driving distance increases by 0.24% when the operating cost declines by 1%. Moreover, from the summary statistics for population density I find that the interquartile range of the rebound effect takes a value of 0.20–0.30, suggesting that the rebound effect is larger in rural areas than

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[9] As shown in Appendix Table A.2, the amounts of the tax cut and the eligibility requirements for the tax incentive measures differ by the implementation period. In addition, the fuel economy standards that are the basis for determining the tax cut and subsidy amounts also changed with the scheme changes.

[10] The second period of the subsidy program was initially scheduled to last until December 2012; however, due to budget constraints, it was completed by September 2012.

[11] Abe et al. (2017) conducted regressions (2.1) by region to analyze the interregional heterogeneity of the rebound effect in Japan.

Table 2: Results of Regressing Driving Demand on Driving Cost

		Dependent variable: $\log M_{ijt}$		
	Coef.	(1)	(2)	(3)
$\log p^M_{jt}$	ρ	0.197	0.335	0.329
		(0.082)	(0.117)	(0.124)
$\log p^M_{jt} \times$ population density	-	-0.174	-0.191	-0.161
		(0.027)	(0.027)	(0.034)
Car characteristics		No	Yes	Yes
Household characteristics		No	No	Yes
R^2		0.087	0.127	0.138
Observations		536	536	536

Note: This table shows the estimation results by OLS. I include horsepower per weight, vehicle size, and the Kei-car dummy as car characteristics and household income, family size, household age, and urban dummy as household characteristics. Heteroskedasticity-robust standard errors are in parentheses.

in urban areas.[12,13] This result provides evidence that there may be interregional heterogeneity in the rebound effect in Japan.

However, the above estimation does not address the endogeneity issue associated with driving costs, so ρ cannot be interpreted as a causal relationship between driving demand and driving cost. For example, if households who frequently use cars tend to purchase fuel-efficient cars to save on the costs of driving, driving demand M_{ijt} should affect driving costs p^M_{jt}. Therefore, the estimates of parameter ρ in Table 2 capture the following two tendencies: the first corresponds to the tendency of households with high driving demand to choose fuel-efficient cars, and the second corresponds to the tendency of an improvement in fuel economy to increase driving demand through the rebound effect. This suggests that I need to carefully consider the choice of car and driving demand to identify the latter effect.

At least two findings emerge from the above simple regression analysis. That is, to assess the impacts of the fuel tax and the purchase incentive while accounting for the rebound effect, it is critical to (i) incorporate two household decisions on car purchase and utilization into a structural

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[12] Data on population density come from Statistical Observations of Municipalities 2013 published by the Statistics Bureau, Ministry of Internal Affairs and Communications, Japan. This data set shows that the population density in units of 10,000 persons/km^2 has a mean of 0.56 and an interquartile range of 0.17–0.83.

[13] Existing literature demonstrates that the rebound effect is smaller in urban areas than in rural areas for several reasons. For example, the income effect generated by lowering the operating cost may lower the rebound effect in urban areas because the income effect is likely to increase demand for buses and trains but not the demand for private cars in areas where public transportation services are extensive. Additionally, more traffic congestion may moderate the rebound effect (Hymel et al., 2010).

model, and (ii) consider the heterogeneity of the rebound effect in designing the model. I explain the methodology in the next section.

3 Model

This section constructs a demand-supply model of the new car market. I begin by describing the demand model, where each household makes two decisions about car purchase and use. For the supply model, I consider differentiated and multiproduct firms that compete in an oligopolistic market in a Bertrand-Nash manner.

3.1 Demand

Following Goldberg (1998) and Bento et al. (2009), I consider a model with two household decisions—car choice and car usage—by using the DCC model developed by Hanemann (1984) and Dubin and McFadden (1984). Specifically, each household makes a car choice decision based on their indirect utility and then decides how far to drive the purchased car; the latter decision is described by a demand function for driving derived from Roy's identity.

Suppose that there are N_t potential households in the automobile market divided by year $t\ (=1,\ldots,T)$. I assume that each year household $i\ (=1,\ldots,N_t)$ decides whether it buys at most one car $j\ (=1,\ldots,J_t)$ or chooses an outside option $(j=0)$, which is not purchasing any of new cars. Let household i has the following indirect utility U_{ijt} conditional on purchasing car j or the outside good in year t:

$$U_{ijt} = V_{ijt} + \varepsilon_{ijt} \tag{3.1}$$

The expression (3.1) implies that household utility consists of V_{ijt} which depends on car and household characteristics, and idiosyncratic household preferences for cars, and ε_{ijt} which captures idiosyncratic shocks. I assume that ε_{ijt} is independently and identically distributed with a type I extreme value distribution.

I specify V_{ijt} in the indirect utility function (3.1) as follows:

$$V_{ijt} = \alpha_i\left(y_i - r_{jt}\right) + \lambda \exp\left(x'_{jt}\beta + h'_i\gamma - \rho_i p^M_{jt}\right) + w'_{jt}\psi + \xi_{jt} \tag{3.2}$$

In the specification, y_i is a household i's income, r_{jt} is a rental price that measures an annualized vehicle purchase price, each of the x_{jt} and w_{jt} is a vector of car attributes, and h_i is a vector of household characteristics.[14] In addition, p^M_{jt} represents the per-kilometer cost of driving, which is defined as the gasoline price p^{gas}_t at the time of purchase divided by car j's fuel economy. The last

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[14] As discussed in a later section, the coefficients for each of the variables (x_{jt}, w_{jt}) are identified with different levels of information in my sample. I include variables that directly affect households' car choice decision into w_{jt} and ones that indirectly affect the choice decision by changing the car usage decision into x_{jt}. This partition is also adopted by Bento et al. (2009), who use different vehicle attributes as each of the components while allowing for

term ξ_{jt} captures car attributes observed by households and firms but unobserved by researchers. The unobserved car attributes include demand shocks, such as advertisements, the brand image of automobile manufacturers, and unmeasured product quality, which are expected to correlate with vehicle prices. Following Berry et al. (1995), I thus deal with the endogeneity issue for rental price r_{jt} in estimation. Note that the utility V_{ijt} depends on the household benefits from car ownership and travel. The middle exponential term in (3.2) corresponds to a utility from car travel as shown in (3.4) below, and the remaining terms that shape a standard form of the indirect utility presumed in the discrete choice literature capture a utility from car ownership. I normalize the indirect utility from the outside option to $U_{i0t} = \alpha_i y_i + \varepsilon_{i0t}$. Appendix A.2 provides the derivation of a direct utility function assumed under the indirect utility specification above.

The utility function includes random coefficients to account for heterogeneous household tastes for car attributes. I specify random coefficients α_i and ρ_i in (3.2) as follows:

$$\alpha_i = \alpha_0 + \alpha_1 y_i + \sigma_\alpha v_{i\alpha},$$
$$\log \rho_i = \rho + \sigma_\rho v_{i\rho}.$$

In the expression for price coefficient α_i, I include household income y_i as a preference shifter to capture the variations in price sensitivity across households with different incomes. I expect the coefficient α_1 to be negative because households with higher incomes are unlikely to sensitively respond to the vehicle price change. The heterogeneity in the operation cost coefficient ρ_i is motivated by the empirical finding of Section 2.3. For each of the coefficient distributions, α_0 and ρ represent the mean parameters, and σ_α and σ_ρ represent the standard deviation parameters. I assume that $v_i = (v_{i\alpha}, v_{i\rho})$ are independently distributed standard normal conditional on demographics.

The indirect utility function above derives the choice probability for alternatives. I assume that households choose an alternative with the highest indirect utility. The household utility net of the idiosyncratic shock ε_{ijt} is rewritten as

$$V_{ijt} = \delta_{jt}(\theta_1) + \mu_{ijt}(\theta_2). \tag{3.3}$$

The terms $\delta_{jt}(\theta_1)$ and $\mu_{ijt}(\theta_2)$ represent a mean utility common to all households and the household-specific utility, respectively. In my specification, $\delta_{jt}(\cdot)$ and $\mu_{ijt}(\cdot)$ for $j = 1, \ldots, J_t$ depend on $\theta_1 = (\alpha_0, \psi)$ and $\theta_2 = (\alpha_1, \lambda, \beta, \gamma, \rho, \sigma_\alpha, \sigma_\rho)$, respectively, and both $\delta_{0t}(\cdot)$ and $\mu_{i0t}(\cdot)$ for the outside option are set to zero as these terms common to all alternatives are eliminated by taking the difference. The distributional assumption on ε_{ijt} yields the probability of household i choosing alternative j $(= 0, 1, \ldots, J_t)$ in year t conditional on household idiosyncratic tastes v_i:

$$\Pr_{ijt} = \frac{\exp\{\delta_{jt}(\theta_1) + \mu_{ijt}(\theta_2)\}}{\sum_{k=0}^{J_t} \exp\{\delta_{kt}(\theta_1) + \mu_{ikt}(\theta_2)\}}$$

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duplication. In fact, this partition is useful from an empirical perspective because some of the vehicle attributes, such as dummies for transmission and make, would directly affect the utility order for discrete vehicle choices, but not the continuous choice for distance traveled.

Finally, I derive the driving demand function for each car purchased. Given purchasing car j in year t, household i determines VKT M_{ijt} subject to the budget constraint,

$$p_{jt}^{M} M_{ijt} + X_{it} = y_i - r_{jt}.$$

The left-hand side of the budget constraint represents the total expenditure for fuel consumption and the Hicksian composite good consumption X_{it}, where the price of the composite good is normalized to one, while the right-hand side represents the residual income after purchasing car j.[15] When household i faces the budget constrain above, applying Roy's identity to the indirect utility function yields the driving demand M_{ijt},[16]

$$\begin{aligned} \log M_{ijt} &= \log\left(-\frac{\partial V_{ijt}/\partial p_{jt}^{M}}{\partial V_{ijt}/\partial y_i}\right) \\ &= \log\left(\frac{\lambda \rho_i}{\alpha_i}\right) + x_{jt}'\beta + h_i'\gamma - \rho_i p_{jt}^{M}. \end{aligned} \tag{3.4}$$

The expression (3.4) implies that the driving demand is explained by vehicle and household characteristics and the cost of driving.

3.2 Supply

I now turn to describe the pricing strategies of car manufacturers. On the supply side, I assume that differentiated, multiproduct firms strategically determine the prices of their products in an oligopolistic market to maximize their profits, given the prices of rival firms' products. From the conditions for profit maximization, I derive pricing equations for each firm that arrive at a Bertrand-Nash equilibrium.

I consider the following profit maximization problem for firms. Let $\mathcal{J}_{ft}$ denote a set of cars that firm f produces in year t. Firm f then determines its prices to maximize variable profit formalized as

$$\sum_{j \in \mathcal{J}_{ft}} \left(p_{jt}^{e} - mc_{jt}\right) N_t s_{jt}(r_t),$$

where p_{jt}^{e} is the tax-exclusive price of car j in year t and $s_{jt}(r_t)$ is the market share obtained under a $J_t \times 1$ vector of tax-inclusive rental prices r_t. The marginal cost mc_{jt} is assumed to be constant in quantity. The first-order condition to be satisfied by p_{jt}^{e} for the profit maximization is given by

$$s_{jt}(r_t) + \left(1 + \tau_{jt}^{ad}\right) \frac{dr_{jt}}{dp_{jt}} \sum_{k \in \mathcal{J}_{ft}} \left(p_{kt}^{e} - mc_{kt}\right) \frac{\partial s_{kt}(r_t)}{\partial r_{jt}} = 0,$$

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[15] To make the normalization, I divide both sides of the budget constraint by the composite good price.

[16] Note that in applying Roy's identity, income y_i that appears in random coefficient α_i is not structurally embedded in the indirect utility but in a reduced form way.

where τ_{jt}^{ad} represents an ad valorem tax. Note that the rental price r_{jt} is a function of the purchase price p_{jt} in the derivation of the first-order conditions above.

I rewrite the J_t first-order conditions in matrix form to obtain pricing equations for each firm. I define a $J_t \times J_t$ matrix S_t, comprising partial derivatives of market share $s_{jt}(r_t)$ with respect to r_{jt} times (-1), and denote the (j,k) element as $S_{jk,t} = -\partial s_{kt}/\partial r_{jt}$. I also define the ownership matrix Ω_t^* with (j,k) element $\Omega_{jk,t}^*$,

$$\Omega_{jk,t}^* = \begin{cases} 1 & \text{if } \exists f \text{ s.t. } \{j,k\} \subset \mathcal{J}_{ft} \\ 0 & \text{otherwise.} \end{cases}$$

With these matrices, I obtain the $J_t \times 1$ vector of tax-exclusive prices p_t^e from the following pricing equation:

$$p_t^e = mc_t + \Omega_t^{-1} s_t^e(r_t) \tag{3.5}$$

In the expression, mc_t is a column vector of marginal costs, $s_t^e(r_t)$ is a column vector with $s_{jt}(r_t)/\{(1+\tau_{jt}^{ad}) dr_{jt}/dp_{jt}\}$ as its jth element, and $\Omega_t = \Omega_t^* \odot S_t$ is a $J_t \times J_t$ matrix, where operator $\odot$ is the element-wise Hadamard product.

4 Estimation and Identification

I lay out the estimation and identification strategies for the model parameters. I rely on a micro likelihood estimation with market share constraint to estimate the DCC model while addressing the car price endogeneity problem (e.g., Goolsbee and Petrin, 2004; Train and Winston, 2007; Goeree, 2008; Benetton, 2021). To identify the model parameters, I employ both micro-level and macro-level moment conditions that come from the household survey and aggregate market data sets.

4.1 Estimation Strategy

I start with an overview of the estimation procedure. I first need to control for product-specific constant terms $\{\delta_{jt}\}_{j,t}$ to address the car price endogeneity problem in estimating the set of parameters (θ_1, θ_2). The sample used in this study, however, includes $\{\delta_{jt}\}_{j,t}$ with over 1,300 elements, leading to a dimensionality problem of the parameter space. Following Berry (1994) and Berry et al. (1995), I circumvent the dimensionality problem by inverting market shares for each car to represent $\{\delta_{jt}\}_{j,t}$ with a function of nonlinear parameters θ_2. I then estimate θ_2 by MLE while concentrating out $\{\delta_{jt}\}_{j,t}$ and use $\{\delta_{jt}\}_{j,t}$ recovered by estimated θ_2 to obtain a consistent estimate of θ_1 by the generalized method of moments (GMM). Based on the estimated demand parameters (θ_1, θ_2), I recover the marginal costs in the supply model.

I proceed with the estimation of demand parameters in two steps. In the first step, I consistently estimate θ_1 for each guess at θ_2. Under the distributional assumption for ε_{ijt}, the predicted market share s_{jt} of car j in year t is expressed by a function of product-specific constants $\{\delta_{jt}\}_j$ and θ_2,

$$s_{jt}(\{\delta_{jt}\}_j, \theta_2) = \int\int \frac{\exp\{\delta_{jt} + \mu_{ijt}(\theta_2)\}}{\sum_{k=0}^{J_t} \exp\{\delta_{kt} + \mu_{ikt}(\theta_2)\}} \, dF(D_i)\, dG(v_i),$$

where $D_i = (y_i, h_i')'$, and $F(\cdot)$ and $G(\cdot)$ denote distribution functions of D_i and v_i, respectively. I compute the multiple integrals in the market share by simulation.[17] I invert the market share function $s_{jt}(\{\delta_{jt}\}_j, \theta_2)$ to obtain the representation for the choice-specific constant terms $\{\delta_{jt}\}_j$ by using the contraction mapping algorithm (Berry, 1994; Berry et al., 1995). Let me denote the market share observed in the data by S_{jt} and define a contraction mapping $T(\delta)$ as

$$T(\delta) = \delta + \log(S_{jt}) - \log(s_{jt}(\{\delta_{jt}\}_j, \theta_2)).$$

This mapping shows that the predicted market share s_{jt} matches the observed market share S_{jt} at a fixed point. I denote the fixed point as $\delta_{jt} = s_{jt}^{-1}(S_{jt}, \theta_2)$.[18] This expression implies that all the product-year fixed effects $\{\delta_{jt}\}_{j,t}$ are represented by a function of parameter θ_2, the estimation of which is described in the next step.

I first estimate θ_1 given a value of θ_2. Recall that in (3.3) δ_{jt} is specified as

$$\delta_{jt} = -\alpha_0 r_{jt} + w_{jt}'\psi + \xi_{jt}. \tag{4.1}$$

I consider an endogeneity problem that is caused by the possible correlation between the rental price r_{jt} and unobserved vehicle characteristics ξ_{jt}. I use the GMM to consistently estimate $\theta_1 = (\alpha_0, \psi)$. Let z_{jt} be a $L \times 1$ vector of instruments that satisfies $E[z_{jt}\xi_{jt}] = 0$. Given parameter θ_2, the GMM estimate of θ_1 is written as

$$\hat{\theta}_1 = \underset{\theta_1}{\operatorname{argmin}}\, \xi' Z W Z' \xi, \tag{4.2}$$

where Z is a $JT \times L$ ($J = \sum_{t=1}^{T} J_t$) matrix for instruments z_{jt}, and ξ is a $JT \times 1$ vector for ξ_{jt}. Additionally, W is an efficient weight matrix that is a consistent estimate of $E[\xi_{jt}^2 z_{jt} z_{jt}']^{-1}$. In the estimation, I implement the two-step GMM by setting $W = (Z'Z)^{-1}$ in the first-stage estimation.

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[17] To approximate the integrals in the market shares, I generate R times random draws from the distributions $F(D_i)$ and $G(v_i)$, where the demographics distribution $F(D_i)$ is constructed based on the CSLC data. With random draws (v_{iD}^r, v_i^r) for $r = 1, \dots, R$, I approximate market share s_{jt} as follows:

$$s_{jt}(\{\delta_{jt}\}_j, \theta_2) \approx \frac{1}{R}\sum_{r=1}^{R} \frac{\exp\{\delta_{jt} + \mu_{ijt}(v_{iD}^r, v_i^r, \theta_2)\}}{\sum_{k=0}^{J_t} \exp\{\delta_{kt} + \mu_{ikt}(v_{iD}^r, v_i^r, \theta_2)\}}.$$

I make $R = 2,000$ random draws from each of the distributions in the estimation.

[18] Given the parameter θ_2, I compute a fixed point for mapping $T(\delta)$ by iterating the following calculation:

$$\delta_{jt}^{h+1} = \delta_{jt}^{h} + \log(S_{jt}) - \log(s_{jt}(\{\delta_{jt}^{h}\}_j, \theta_2)).$$

I define the fixed point as the convergent point when iterating the calculation above until $\|\delta_{jt}^{h+1} - \delta_{jt}^{h}\|_\infty < \epsilon^{tol}$ is satisfied, where the tolerance criterion ϵ^{tol} is set at 10^{-12}.

In the second step, I estimate θ_2 by maximizing a likelihood function that is constructed based on individual car choice and mileage choice. Let $\tilde{M}_{ijt}$ denote the observed annual mileage and η_{ijt} be the measurement error that explains the difference between the logs of observed and predicted mileage,

$$\eta_{ijt} \equiv \log \tilde{M}_{ijt} - \log M_{ijt}.$$

I assume that η_{ijt} is distributed as a normal distribution with mean zero and variance σ_η^2. It then follows that the conditional density of the observation $\tilde{M}_{ijt}$ takes the form

$$\ell\left(\log \tilde{M}_{ijt} \middle| d_{ijt} = 1,\ j \neq 0\right) = \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left\{-\frac{1}{2}\left(\frac{\log \tilde{M}_{ijt} - \log M_{ijt}}{\sigma_\eta}\right)^2\right\},$$

where d_{ijt} is an indicator variable equal to one when household i chooses alternative j ($j = 0, 1, \ldots, J_t$) in year t and zero otherwise. In addition, $\log M_{ijt}$ on the right-hand side is given by (3.4). The likelihood function for each household is written by

$$L_{ijt}(\tilde{\theta}_2) = \left[\int \mathrm{Pr}_{i0t}\, dG(v_i)\right]^{d_{i0t}} \cdot \prod_{j=1}^{J_t} \left[\int \mathrm{Pr}_{ijt} \cdot \ell\left(\log \tilde{M}_{ijt} \middle| d_{ijt} = 1\right)\, dG(v_i)\right]^{d_{ijt}},$$

where $\tilde{\theta}_2 = (\theta_2, \sigma_\eta)$. The likelihood $L_{ijt}(\tilde{\theta}_2)$ for household i comprises the choice probability of an alternative and the density of mileage conditional on purchasing a car, forming the joint probability of car choice and use. It allows me to jointly estimate parameters in the demand equations for cars and mileage. I approximate the integrals in the likelihood function L_{ijt} by simulation and use $\check{L}_{ijt}$ to denote the simulated likelihood function. Consequently, the simulated log-likelihood function to be maximized is given by

$$\sum_{t=1}^{T} \sum_{i=1}^{N_t} \log \check{L}_{ijt}(\tilde{\theta}_2).$$

I maximize the objective function over the nonlinear parameters $\tilde{\theta}_2$, by replacing θ_1 with the GMM estimate $\hat{\theta}_1$ obtained from (4.2) for each guess of θ_2.

Finally, I estimate marginal cost mc_{jt} in the supply model. Based on the estimated demand parameters, marginal costs are obtained by rearranging the pricing equation (3.5),

$$\widehat{mc}_t = p_t^e - \Omega_t^{-1} s_t^e(r_t).$$

On the left-hand side of the expression, $\widehat{mc}_t$ is a $J_t \times 1$ vector of estimated marginal costs in year t.

4.2 Identification

The identification of the demand parameters (θ_1, θ_2) comes from distinct levels of moments contained in the data sets. The expression (3.3) implies that the availability of micro data, such as household survey data in this study, allows me to identify the set of parameters (δ_{jt}, θ_2) without any assumptions on observed and unobserved vehicle characteristics (Berry et al., 2004). On the other hand, I need product-level data and some distributional assumptions on those vehicle characteristics to identify θ_1 that governs substitution patterns among vehicles.

I face a price endogeneity problem in estimating θ_1 based on the regression (4.1). In the automobile market, many cases are observed where vehicle models with a high market share are sold at higher prices. This fact allows me to interpret it as automobile manufacturers assigning high prices to high-quality vehicles, leading to a positive correlation between the vehicle price and attributes unobserved by researchers. Hence, neglecting the price endogeneity problem would bias the marginal disutility of price toward a positive direction.

Note here that the price coefficient common to all households, α_0, is identified based on equation (4.1) since it is primitively derived from the relationship between the quantity demanded for vehicles and the rental prices. I thus estimate α_0 using (4.1) before carrying out MLE. On the other hand, I estimate α_1, the preference shifter in α_i, together with all other parameters $\tilde{\theta}_2$ in MLE after retrieving θ_1 in GMM estimation because the model allows for the dependence of the distance traveled M_{ijt} on household income y_i, which enters the driving demand function (3.4) in a reduced form way.

Following Berry et al. (1995), I use an instrumental variable approach to address the price endogeneity problem. I base estimation on the moment conditions $E[\xi_{jt}|z_{jt}] = 0$, where z_{jt} is a vector of instruments. For the instrumental variables, I adopt tax-location instruments following Konishi and Zhao (2017) and Kitano (2022). The tax-location instruments are constructed by the amounts of tax reduction and subsidy applied under the purchase incentive for each vehicle. There are two advantages to using the tax-location instruments. First, tax reduction amounts under the Japanese purchase incentive are determined by some vehicle attributes including fuel economy, weight, and engine displacement. Therefore, I expect the tax reduction amounts to be uncorrelated with the unobserved vehicle attributes ξ_{jt} after controlling for the vehicle attributes, satisfying the exclusion restriction. Second, because the Japanese purchase incentive experienced several scheme changes during the sample period, the tax reduction and subsidy amounts vary across vehicles and over time, as shown in Section 2.2. This implies that the tax-location instruments have two-dimensional variations for the identification of demand parameters.

I construct the tax-location instruments in the same way as the BLP instruments (Berry et al., 1995). Specifically, I form the instruments based on the sum of the tax reduction and subsidy amounts applied to vehicles produced by the same producer and the sum of those applied to vehicles produced by the other producers.[19] I further include the per-kilometer cost of driving p^M_{jt} and other

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[19] I exclude the tax reduction and subsidy amounts themselves from the tax-location instruments because of their performance in the first-stage estimation. In addition, as the tax reduction amounts I only use those of the tonnage tax and automobile tax because as Kitano (2022) notes, the acquisition tax is an ad valorem tax and fails to satisfy the exclusion restriction.

vehicle attributes w_{jt} in the instruments z_{jt} as these are assumed to be exogenous in my setting. For comparison purposes, I also use BLP instruments in estimation. In the next section, the empirical results show that the tax-location instruments perform well in the first-stage estimation relative to the BLP instruments.

Unlike parameter θ_1, θ_2 appears not only in the utility function but in the driving demand function. Thus, θ_2 is identified from the joint distribution of car ownership, use, and household demographics. For the identification of random coefficients, I need individual data on car choice, distance traveled, and household characteristics. I then use micro-moments on such information in the household survey to identify household heterogeneous preference. In addition, I deal with the simultaneity issue that can be caused in estimating coefficient $\rho \in \theta_2$ as discussed in Section 2.3 by controlling for unobservables that affect both demands for cars and use through random coefficients.

On the supply side, the identification of marginal cost mc_{jt} relies on that of the demand parameters. In particular, the marginal costs are identified from the variations in car price and market share across models and years.

5 Empirical Results

In this section, I present the estimation results for the demand and supply models. Table 3 summarizes the estimated demand parameters. In the empirical estimation, I use horsepower per weight, vehicle size, the Kei-car dummy, and other dummies as car attributes and family size, age of household head, and the urban dummy as household demographics. Panel A in Table 3 reports the results of the regression of δ_{jt} by GMM with the BLP instruments and the tax-location instruments. I find that the tax-location instruments provide a sufficiently large F statistic in the first-stage estimation, and the estimates of the rental price coefficient α_0 obtained using each instrument are similar and statistically significant. In addition, the results indicate that the demand for mini-vehicles (Kei-cars) is high relative to regular vehicles, while the demand for regular vehicles tends to be higher for vehicles with greater size. Panel B reports the results of estimating the DCC by MLE. The results show that all the estimates of coefficients have the expected signs. Since the coefficients of horsepower per weight and vehicle size have positive signs, this suggests that as engine power and vehicle size increase, the demand for driving increases. By contrast, the estimate of the coefficient of the Kei-car dummy has a negative sign, which reflects the fact that households tend not to drive long distances in mini-vehicles.

The estimation result also demonstrates the heterogeneity in rebound effects. Indeed, Panel B in Table 3 finds that both the estimates of the mean and variance parameters, ρ and σ_ρ, of the random coefficient ρ_i are statistically significant. Figure 2 displays the estimated distribution of the rebound effect. The average rebound effect is 0.09, indicating that a 1% decrease in the per-kilometer cost of driving will increase driving demand by 0.09%. Figure 2 also confirms that the

Table 3: Estimation Results

	Coef.	(1) Est.	(1) S.E.	(2) Est.	(2) S.E.
Panel A. Linear parameter estimates by GMM					
Rental price	α_0	11.799	0.754	11.208	0.759
Constant	ψ_1	-21.743	1.471	-21.004	1.500
Horsepower per weight	ψ_2	31.651	5.037	30.123	5.067
Size	ψ_3	12.352	1.934	10.857	1.969
Kei-car dummy	ψ_4	36.091	3.139	34.794	3.166
AT/CVT	ψ_5	1.154	0.420	1.050	0.423
Hybrid dummy	ψ_6	1.419	0.294	1.389	0.295
Maker dummies		Yes		Yes	
Year dummies		Yes		Yes	
Instrumental variables		BLP IV		Tax-location IV	
First-stage F statistic		28.6		79.9	
Hansen J statistic (d.f.)		16.4 (8)		1.7 (2)	
Panel B. Non-linear parameter estimates by MLE					
Rental price × income	α_1	-0.232	0.025	-0.222	0.012
Rental price (Std. Dev.)	σ_α	1.202	0.136	1.138	0.057
Constant	λ	1.932	0.311	1.991	0.333
Horsepower per weight	β_1	0.670	0.412	0.577	0.388
Size	β_2	1.705	0.172	1.716	0.164
Kei-car dummy	β_3	-0.140	0.250	-0.148	0.232
Family size	γ_1	1.882	0.427	1.770	0.435
Age of household head	γ_2	-1.716	0.264	-1.643	0.364
Urban dummy	γ_3	0.946	0.106	0.910	0.103
Cost of driving per kilometer	ρ	-0.357	0.155	-0.447	0.138
Cost of driving per kilometer (Std. Dev.)	σ_ρ	0.793	0.006	0.789	0.006
Error term in the driving demand eq. (Std. Dev.)	σ_η	0.020	0.004	0.019	0.004
Log-likelihood		-7.560		-7.561	
Observations in the aggregate data set		1,302		1,302	
Observations in the household survey		548		548	

Note: The estimation results by GMM and MLE are reported in Panel A and B, respectively. The estimations are run with the family size measured per 100 persons, the age of household head, Kei-car dummy, and urban dummy multiplied by 0.001, 0.1, and 0.1, respectively. For the other variables, I use the units listed in Table 1.

rebound effect is unevenly distributed across households, with an interquartile range of 0.07–0.11%. Compared with the structural estimate, I find that the OLS counterpart shown in Section 2.3 is biased upward and significantly overestimates the rebound effect in absolute value. The rebound

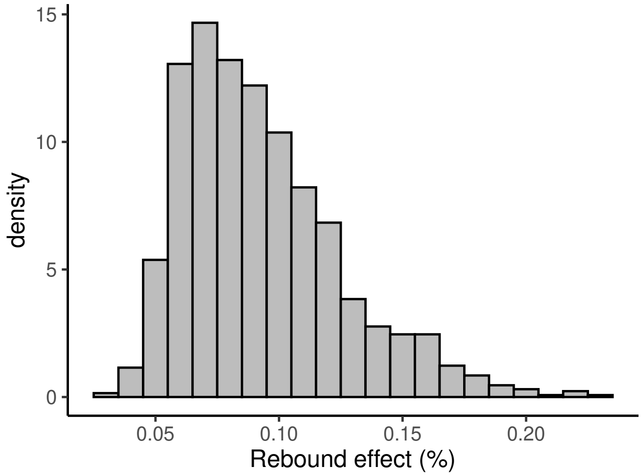

Figure 2: Heterogeneity of the Rebound Effect

Note: This figure shows the histogram of the estimated rebound effect. Based on the estimates from model 2 in Table 3, I evaluate the rebound effect by calculating the elasticity of driving demand with respect to the driving cost, $\frac{\partial M_{ijt}}{\partial p^M_{jt}} \frac{p^M_{jt}}{M_{ijt}} = -\rho_i p^M_{jt}$, and integrating it over the distribution of household idiosyncratic preference $v_{i\rho}$.

effect estimate of this study falls in the range of estimates obtained in the most recent studies in developed countries (Graham and Glaister, 2002; Gillingham et al., 2016).[20] In particular, my estimate which is obtained by combining the household-level cross-sectional data and the market-level panel data is comparable to the estimate of Gillingham et al. (2015), who estimate a short-run rebound effect of 0.10 using a very large individual-level panel data set in a US state.[21]

Table 4 describes the summary statistics of estimated own-rental price elasticities, marginal costs, and markups. Here, I calculate the own- and cross-rental price elasticities of market share as follows:

$$\frac{\partial s_{jt}}{\partial r_{kt}} \frac{r_{kt}}{s_{jt}} = \begin{cases} -\frac{r_{jt}}{s_{jt}} \int\int \alpha_i s_{ijt}(1 - s_{ijt})\, dF(D_i)\, dG(v_i) & \text{if } j = k, \\ \frac{r_{kt}}{s_{jt}} \int\int \alpha_i s_{ijt} s_{ikt}\, dF(D_i)\, dG(v_i) & \text{otherwise.} \end{cases}$$

where $s_{ijt} = \exp(V_{ijt}) \big/ \sum_{k=0}^{J_t} \exp(V_{ikt})$. Table 4 reports that the estimated own-rental price elasticity is -4.68 on average. In addition, the estimated markups are, on average, approximately 27%. These estimates are comparable to those found in Berry et al. (1995) and Grigolon et al. (2018) using data from the United States and European countries, respectively.

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[20] Gillingham et al. (2016) review recent empirical studies on the rebound effect and conclude that the short- and medium-run elasticities of gasoline/driving demand with respect to gasoline price in developed countries fall in the range from 0.05 to 0.25.

[21] Gillingham et al. (2015) estimate the gasoline price elasticity of driving demand.

Table 4: Elasticities, Marginal Costs, and Markups

	Mean	Std. Dev.	1st Q.	3rd Q.
Own-rental price elasticities of demand	-4.68	2.01	-5.48	-3.30
Marginal costs (in millions of JPY)	1.85	1.61	0.86	2.16
Markups	0.27	0.10	0.20	0.34

Note: This table summarizes descriptive statistics for price elasticities, marginal costs, and markups for vehicles sold during the sample period, 2006–2013. The markups are defined as $(p - mc)/p$. The 1st Q. and 3rd Q. stand for the first and third quantiles.

Table 5: List of Counterfactual Scenarios

Scenarios	Fuel tax	Purchase incentive
[1] Baseline	0	-
[2] Fuel tax at the Pigouvian tax rate	4,000	-
[3] Fuel tax at current tax rate in Japan	21,603	-
[4] Actual purchase incentive	0	attribute-based rebate program
[5] Registration subsidy	0	emissions-based rebate program
[6] Registration tax	0	emissions-based tax increase program

Note: The unit of the fuel tax is JPY per ton of CO_2.

6 Counterfactual Analysis

Based on the estimated parameters, I examine the efficiency and distributional effects of the fuel tax and the purchase incentive. I first describe the policy scenarios considered in counterfactual analyses and then show the welfare effects and value the shadow costs of their implementation. Finally, I conduct a decomposition analysis of CO_2 emissions to demonstrate the contribution of the rebound effect to environmental externalities arising under policy scenarios.

6.1 Scenarios

The policy scenarios that I consider in the counterfactuals are summarized in Table 5. I compare the baseline scenario with two fuel tax scenarios with different tax rates and three purchase incentive scenarios which include alternative purchase incentives, such as emissions-based registration subsidy and registration tax, as well as the actual purchase incentive scheme. To do so, I first simulate a baseline scenario in which neither fuel tax nor purchase incentives are enforced, using model parameters estimated in the previous section. The remaining scenarios are then introduced into the baseline to assume situations in which fuel taxes and purchase incentives take effect during the sample period in Japan.

6.1.1 Fuel Taxes

In the second and third scenarios, I consider situations in which fuel taxes at the same rate as the social cost of carbon (SCC) and the current tax rate in Japan are added to the pre-tax prices.

I first briefly outline the fuel tax situation in Japan. There has long been a fuel tax of 55.84 JPY/L for gasoline. Beginning in October 2012, the Japanese government phased in a carbon tax in addition to the pre-existing fuel tax. The rate of the newly introduced carbon tax has been gradually raised and set at 0.76 JPY/L (289 JPY/ton of CO_2) since 2016.[22] Thus, the price of gasoline p_t^{gas} that households face in year t is written as

$$p_t^{gas} = p_t^{pre\text{-}tax} + \tau^{gas} + \tau^{carbon},$$

where

- $p_t^{pre\text{-}tax}$ is the pre-tax price of gasoline in year t,
- τ^{gas} is the pre-existing gasoline tax rate of 55.84 JPY/L, and
- τ^{carbon} is the carbon tax rate of 0.76 JPY/L.[23]

Since the price of gasoline averages approximately 150 JPY/L during the sample period, the current gasoline tax rate of 56.6 JPY/L accounts for approximately one-third of the gasoline price.

The second scenario in the simulation is for analyzing the welfare implication of the Pigouvian tax for fuels in the automobile market. In the scenario, I impose the SCC of 4,000 JPY/ton of CO_2 (10.48 JPY/L), which is approximately 40 USD/ton of CO_2, on the pre-tax price of fuels $p_t^{pre\text{-}tax}$.[24,25] In the third scenario, I explore the effect of the fuel tax using the current tax rate in Japan of 21,603 JPY/ton of CO_2 (56.6 JPY/L).

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[22] The carbon tax rate has reached the current level in two phases. For example, the carbon tax rate for petroleum was set to 95 JPY/ton of CO_2 (0.25 JPY/L) from October 2012 to March 2014, 190 JPY/ton of CO_2 (0.5 JPY/L) from April 2014 to March 2016, and 289 JPY/ton of CO_2 (0.76 JPY/L) from April 2016.

[23] The pre-existing gasoline tax τ^{gas} is divided into a petroleum and coal tax levied upstream and a gasoline tax and a local gasoline tax levied downstream. The rate of the petroleum and coal tax τ^{petrol} is 779 JPY/ton of CO_2 (2.04 JPY/L), and the sum of the rates of the gasoline tax and the local gasoline tax amounts to 23,173 JPY/ton of CO_2 (53.8 JPY/L). The diesel fuel is subject to a diesel handling tax τ^{diesel} of 32.1 JPY/L. For expositional simplicity, I omit the excise tax τ^{ex} on fuel prices in the main body of the paper. In practice, gasoline and diesel prices, p_t^{gas} and p_t^{diesel}, are calculated as follows:

$$p_t^{gas} = \left(p_t^{pre\text{-}tax} + \tau^{gas} + \tau^{carbon}\right) \times (1 + \tau^{ex})$$

and

$$p_t^{diesel} = \left(p_t^{pre\text{-}tax} + \tau^{petrol} + \tau^{carbon}\right) \times (1 + \tau^{ex}) + \tau^{diesel}.$$

I use these formulas in the analysis.

[24] The SCC comes from IWG (2016) and corresponds to the estimate for 2020 that is calculated with a discount rate of 3%.

[25] I set both the pre-existing gasoline tax τ^{gas} and the carbon tax τ^{carbon} to zero in this scenario.

6.1.2 Purchase Incentives

In the remaining scenarios, I study three kinds of purchase incentive schemes that include one actually implemented in Japan and alternative ones.

Actual Purchase Incentive The actual purchase incentive scenario corresponds to a situation where the purchase incentive implemented in Japan during the sample period is introduced into the baseline scenario. As described in Section 2.2, the Japanese purchase incentive is essentially a rebate program, consisting of a tax incentive measure and a subsidy program for fuel-efficient vehicles. Here, let T_{jt} denote a vector of automobile-related taxes and $p(p^e_{jt}, T_{jt})$ denote a function of the tax-exclusive vehicle price p^e_{jt} and T_{jt} that represents the total amount of taxes paid by a new car purchaser at the time of purchase. Appendix A.1.1 provides the details on automobile-related taxes during the sample period in Japan. With these notations, the tax-inclusive vehicle price p_{jt} under the actual purchase incentive scenario is written as

$$p_{jt} = p^e_{jt} + p\left(p^e_{jt}, tr_{jt} \cdot T_{jt}\right) - ES_{jt},$$

where tr_{jt} and ES_{jt} represent a vector of tax reduction rates for automobile-related taxes and the amount of subsidy for fuel-efficient cars, respectively. The tax reduction rates and the subsidy amount are determined by the achievement rates for the fuel economy standards set by vehicle weight (see Appendix A.1 for details). I convert the tax-inclusive price p_{jt} calculated by the expression above into the rental price r_{jt} paid annually by households during their car ownership in measuring household utility, which allows me to compare the welfare consequence of the purchase incentive with that of the fuel tax levied annually on fuel consumption.

Alternative Purchase Incentives I also consider alternative purchase incentives, emissions-based registration subsidy and tax. Specifically, each of them determines the annual amounts of subsidy and tax based solely on the vehicle's CO_2 emissions per kilometer. Under the registration subsidy and the registration tax scenarios, the tax-inclusive prices p_{jt} are determined as follows:

$$p_{jt} = p^e_{jt} + p\left(p^e_{jt}, T_{jt}\right) - \tau^E \cdot \frac{1}{e_{jt}},$$

and

$$p_{jt} = p^e_{jt} + p\left(p^e_{jt}, T_{jt}\right) + \tau^E e_{jt}.$$

Here, τ^E represents the subsidy/tax rates in each scenario, and e_{jt} represents CO_2 emissions per kilometer from driving car j in year t.[26] For purposes of comparison with the other policy scenarios,

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[26] Per-kilometer CO_2 emissions e_{jt} (kg-CO_2/km) are defined as fuel economy divided by the CO_2 emission factor per liter of fuel consumption. The CO_2 emission factor per liter of gasoline (diesel) is 2.322 kg-CO_2/L (2.621 kg-CO_2/L), which is obtained by multiplying the calorific value per liter of gasoline, 34.6 MJ/L (38.2 MJ/L), by CO_2 emission factor per calorific value of gasoline, 0.0671 kg-CO_2/MJ (0.0686 kg-CO_2/MJ).

I set the subsidy/tax rates τ^E such that the registration subsidy and the registration tax achieve the same environmental externalities as the actual purchase incentive and the current fuel tax, respectively.

6.2 Evaluating Social Welfare

I evaluate the welfare effects of policies in the equilibrium of the automobile market. To calculate equilibrium prices, I exploit the method proposed by Morrow and Skerlos (2011).[27] Appendix A.3 provides the detail for the computation of equilibrium prices. Given estimated equilibrium prices, I evaluate policies using four measures of surplus: consumer surplus (CS), producer surplus (PS), tax revenues (TR), and environmental externalities (EXT). Following Small and Rosen (1981), the change in expected consumer surplus due to a policy change is calculated as follows:

$$\Delta E(CS) = N_t \int\int \frac{1}{\alpha_i}\left[\log\left\{\sum_{j=0}^{J_t}\exp\left(V_{ijt}^1\right)\right\} - \log\left\{\sum_{j=0}^{J_t}\exp\left(V_{ijt}^0\right)\right\}\right] dF(D_i)\, dG(v_i),$$

where V_{ijt}^0 and V_{ijt}^1 represent the indirect utility under the baseline scenario and after a policy change, respectively. In addition, the other measures of surplus are calculated as follows:

$$\begin{aligned} PS &= \sum_{f\in\mathcal{F}}\sum_{j\in\mathcal{J}_{ft}}\left(p_{jt}^e - \widehat{mc}_{jt}\right) N_t s_{jt}(r_t), \\ TR &= \int\int\sum_{f\in\mathcal{F}}\sum_{j\in\mathcal{J}_{ft}}\left(p\left(p_{jt}^e, tr_{jt}\cdot T_{jt}\right) - ES_{jt} + T_{ijt}^{fuel}\right) N_t s_{ijt}(r_t)\, dF(D_i)\, dG(v_i), \\ EXT &= \text{SCC}\times\int\int\sum_{f\in\mathcal{F}}\sum_{j\in\mathcal{J}_{ft}} e_{jt}M_{ijt}N_t s_{ijt}(r_t)\, dF(D_i)\, dG(v_i), \end{aligned}$$

where T_{ijt}^{fuel} in the second expression represents the fuel tax amount from household i's driving of car j in year t, and SCC in the last expression denotes the value of the SCC.[28] In the second expression, the tax revenues consist of the sum of tax revenues from the automobile-related taxes and fuel taxes minus resources used for the purchase incentives. Consequently, I define the sum of the above as the total surplus (TS).

6.3 Simulation Results

In this section, I examine the impacts each policy has on the market outcomes and social welfare.

6.3.1 Policy Impacts on Outcome Variables

Table 6 reports the values of some outcome variables for vehicles sold in 2012 obtained under each policy scenario. The table first shows that fuel taxes are less likely to affect the equilibrium prices

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[27] See Conlon and Gortmaker (2020) for the advantages of this method.

[28] The amount of fuel tax T_{ijt}^{fuel} is calculated by $(M_{ijt}/fe_{jt})(\tau^{gas}+\tau^{carbon})$, where fe_{jt} is the fuel economy (km/L).

Table 6: Impacts of Policies on Various Outcomes in 2012

Scenarios	Tax-excl. price p^e_{jt} (mil. JPY)	Tax-incl. price p_{jt} (mil. JPY)	Sales (1,000)	Fuel economy (km/L)	VKT (Tm)	Fuel usage (GL)
[1] Baseline	2.3780	2.6720	3,875	20.51	22.55	1.25
[2] Pigouvian fuel tax	2.3781	2.6721	3,777	20.57	21.51	1.18
[3] Current fuel tax in Japan	2.3784	2.6724	3,377	20.83	17.57	0.95
[4] Actual purchase incentive	2.3819	2.5938	4,938	21.24	28.65	1.53
[5] Registration subsidy	2.3755	2.6693	5,039	21.22	28.75	1.53
[6] Registration tax	2.3846	2.6792	2,957	20.94	17.45	0.95

Note: This table shows the average tax-exclusive and tax-inclusive prices, total sales, the sales-weighted average of fuel economy, aggregate VKT, and aggregate fuel usage obtained under each scenario using the sample for 2012.

of automobiles, which is consistent with the results of Grigolon et al. (2018) and Tan et al. (2019). Meanwhile, the fuel tax at the current tax rate moderates aggregate VKT by 22% relative to the baseline scenario, resulting in an additional reduction of fuel usage with the improvement of the average fuel economy of purchased vehicles. Indeed, the sales-weighted average of fuel economy in 2012 in the current fuel tax scenario is 20.83km/L, which is 1.6% higher than that obtained in the baseline scenario.

In contrast, the purchase incentive actually implemented in Japan leads to significant impacts on the market outcomes. Table 6 shows that compared to the baseline scenario the actual purchase incentive raises the average equilibrium tax-exclusive price by 0.16% and the total sales by 27%, and the sales-weighted average of fuel economy by 3.6%. It is noticeable that while the aggregate fuel consumption under the purchase incentive scenario increases relative to the baseline, its increase rate is lower than that of the total sales. I will scrutinize the channels through which the purchase incentive changes fuel consumption in Section 6.4.

Table 6 also presents the impacts of the alternative purchase incentives on outcomes. I perform a grid search to obtain the rate of subsidy/tax τ^E for each alternative scheme.[29] Under the calculated subsidy rate, the registration subsidy achieves the same fuel usage as the actual purchase incentive without entailing a reduction in sales volumes. On the other hand, compared the registration tax and the current fuel tax, the former considerably decreases sales to keep the fuel usage at the same

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[29] For the registration subsidy, τ^E works out to 15,311 JPY per kg-CO_2 per kilometer such that the registration subsidy achieves the same externality as the actual purchase incentive, and for the registration tax, 1.21 million JPY per kg-CO_2 per kilometer such that the registration tax achieves the same externality as the current fuel tax rate. Under these subsidy/tax rates, the registration subsidy scheme provides new car purchasers with subsidies of 45,505–233,459 JPY with an average of 107,489 JPY, and the registration tax scheme imposes tax burdens of 79,044–405,532 JPY with an average of 190,632 JPY.

level as the latter. This is because reducing the sales volumes is the only way for the registration tax to control the fuel consumption, while the fuel tax is able to achieve the same objective by directly controlling driving demand.

Here, in addition to the effects of the assumed policy scenarios, I analyze how outcome variables will change with the increase in a fuel tax in the future. In this experiment, I assume a situation in which some fuel taxes are added to the current fuel tax rate of 21,603 JPY/ton of CO_2. Appendix Figure A.1 displays the effects on sales, VKT, and CO_2 emissions, showing that the additional fuel tax of 10,000 JPY/ton of CO_2 (which corresponds to the increase in fuel price of 26.2 JPY/L from the current level) leads to 5.3%, 9.1%, and 10.1% declines in total sales, aggregate VKT, and CO_2 emissions relative to each reference point, respectively. In particular, the result suggests that the elasticity of CO_2 emissions with respect to the fuel tax is around -0.22% in Japan.

6.3.2 Welfare Effects

I next investigate the welfare effects of each assumed policy. Table 7 shows the results using the sample for 2012, with the welfare obtained in the baseline scenario in the first row and changes in welfare associated with policy changes from the baseline in the remaining rows. I first confirm that under the Pigouvian fuel tax scenario the fuel tax revenue almost equates to the environmental externality, indicating that the Pigouvian fuel tax completely offsets the negative externality arising from car driving. Meanwhile, the fuel tax decreases the consumer and producer surplus compared to the baseline scenario, leading to the decline in the total surplus. I find that the major part of the decline in consumer surplus comes primarily from the reduction in the driving demand due to the tax because the estimate of the rebound effect obtained in the previous section implies less elastic demand for driving with respect to the driving cost and thus the decrease in consumer surplus due to the driving demand reduction should be of roughly the same magnitude as the fuel tax revenue which is approximately 12 billion JPY. Table 7 also shows that fuel taxes effectively reduce the environmental externality with low tax resources. Indeed, while the fuel tax with the current tax rate in Japan increases the tax burden on consumers, which corresponds to the tax revenues, by approximately 5% compared to the baseline, it reduces the environmental externality by 24%.

In addition, it turns out that the fuel tax at the current tax rate achieves a significantly higher total surplus than the registration tax. In particular, the registration tax substantially reduces the consumer and producer surplus and increases the tax burdens to achieve the same environmental externality as the fuel tax, which is consistent with the results presented in Table 6. Table 7 suggests that the fuel tax is approximately 1.7 times more efficient than the externality-equivalent registration tax.

In contrast to the fuel taxes, the actual purchase incentive raises the total surplus by 591 billion JPY in 2012 relative to the baseline scenario.[30] Table 7 shows that a significant majority

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[30] Table 7 confirms the validity of the estimated total expenditure on the purchase incentive. The government

Table 7: Welfare Effects in 2012 (in billions of JPY)

Scenarios	CS	PS	TR Automobile-related taxes	TR Fuel tax	TR Incentives	EXT	TS
[1] Baseline (in levels)	487	1,824	276	0	0	11.6	2,575
[2] Pigouvian fuel tax	-13	-48	-8	+12	±0	-0.6	-57
[3] Current fuel tax in Japan	-67	-246	-40	+53	±0	-2.8	-296
[4] Actual purchase incentive	+134	+552	+79	±0	-172	+2.6	+591
[5] Registration subsidy	+145	+492	+66	±0	-165	+2.6	+535
[6] Registration tax	-116	-419	-66	±0	+97	-2.8	-501

Note: The first row lists the welfare under the no-policy baseline scenario, and the remaining rows list changes in welfare associated with policy changes from the no-policy baseline. The sum of the tax revenue amounts from automobile-related taxes and the purchase incentives refer to the annualized amounts paid by car owners over the ownership duration as a part of the rental price, not the lump sum amounts paid at the time of purchase.

of this welfare gain comes through increases in consumer and producer surplus. I believe this is attributable to the fact that the pre-existing automobile-related taxes already result in a deadweight loss in the automobile market, and the purchase incentive plays a role in mitigating the market distortions (Buchanan, 1969; Fowlie et al., 2016). Table 7 also shows that the actual purchase incentive results in a higher total surplus than the externality-equivalent registration subsidy. This result comes from higher producer surplus and tax revenue from automobile-related taxes. In fact, the actual purchase incentive provides substantial tax credits to large-sized cars with high emissions compared to the registration subsidy that determines the amounts of subsidy depending solely on vehicle CO_2 emissions per kilometer. Consequently, the actual purchase incentive becomes costly to achieve a certain amount of environmental externality than the registration subsidy. On the other hand, the consumer surplus is in turn found to be higher for the registration subsidy than the actual purchase incentive. In the next section, I will investigate the effects that each policy have on consumer welfare by income group.

6.3.3 Distributional Impacts

I examine the distributional impacts of each policy. In particular, I study how costs associated with policy implementation incurred by households differ across income groups and compare the distributional equity of each policy based on the estimated shadow costs.

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expenditure on the purchase incentive of 172 billion JPY reported in Table 7 implies that the estimated total expenditure in 2012 amounts to about 630 billion JPY, which is almost comparable to the actual expenditures on the tax incentive measures and the subsidy program. Note that because the subsidy program in the second period was completed by September 2012 due to budget constraints, the estimate indicates a higher amount than the actual value.

Table 8: Shadow Costs of Policy Implementation

Income quintile	Fuel tax: $\lvert\Delta\mathrm{CS}\rvert/\mathrm{CO}_2$ ton (JPY)	Fuel tax: $\lvert\Delta\mathrm{CS}\rvert$/income	Registration tax: $\lvert\Delta\mathrm{CS}\rvert/\mathrm{CO}_2$ ton (JPY)	Registration tax: $\lvert\Delta\mathrm{CS}\rvert$/income
1 (lowest)	97,075	2.47	169,321	5.25
2	94,555	1.43	164,955	2.89
3	93,825	1.09	163,526	2.10
4	94,846	0.96	163,113	1.76
5 (highest)	93,503	1.25	161,685	1.83

Note: The table presents the change in consumer surplus as a percentage of CO_2 reduction and that as a percentage of income due to the implementation of the fuel tax at the current tax rate (21,603 JPY/ton of CO_2) and the externality-equivalent registration tax in 2012 by income quintile. $\lvert\Delta\mathrm{CS}\rvert$ represents the absolute value of the change in consumer surplus from the no-policy baseline.

Appendix Figure A.2 displays the change rates of sales, VKT, and fuel economy by income quintile when each policy is introduced into the baseline scenario. Three figures on the top panel show that the distributional impacts considerably differ between the fuel tax and the registration tax. The fuel tax reduces sales volume and VKT equally across all income groups, while the registration tax reduces them particularly on lower income groups. As for the fuel economy, the fuel tax induces particularly high-income households to improve their fuel economy. This fact indicates that high-income households that drive long distances particularly react to the introduction of the fuel tax by replacing fuel-inefficient vehicles with fuel-efficient vehicles to save on driving costs. Because low-income households already own fuel-efficient vehicles such as Kei-cars before the tax imposition, the improvement in average fuel economy in low-income groups is relatively small. In contrast, I find that the registration tax requires low-income households as well to improve the fuel economy to the same extent as high-income households.

Appendix Figure A.2 on the bottom panel depicts the change rates for the actual purchase incentive and the registration subsidy. It is remarkable that while both two policies increase the sales in all income classes, the registration subsidy particularly drives up sales in low-income classes relative to the actual purchase incentive. This is attributable to the fact that the registration subsidy is designed to provide fuel-efficient vehicles such as Kei-cars that low-income households tend to purchase with substantial subsidies.

I next value the shadow costs of the fuel tax and the registration tax and investigate how their real tax burdens measured by the shadow costs differ across households. Table 8 reports the results by income quintile. The first and third columns in the table present the changes in consumer surplus as a percentage of CO_2 reduction due to the implementation of the fuel tax with the current tax rate and the externality-equivalent registration tax, respectively. These figures measure a shadow

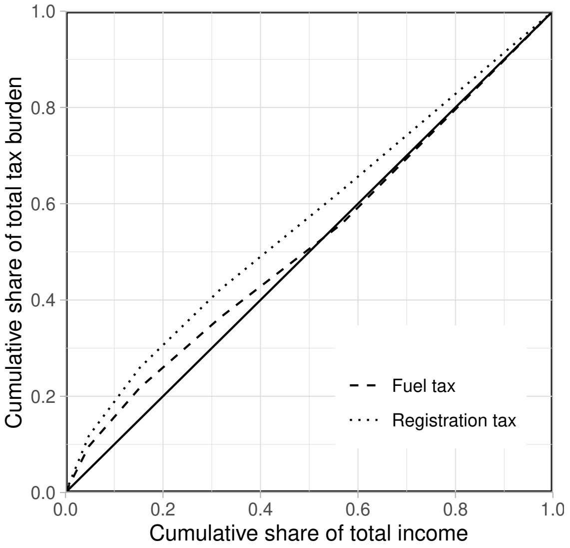

Figure 3: Regressivity of the Fuel Tax and the Registration Tax

Note: The figure depicts the Lorenz curves for the fuel tax at the current tax rate and the externality-equivalent registration tax, along with the 45-degree line (solid line). The total tax burden plotted on the vertical axis is measured by the change in consumer surplus associated with policy changes from the no-policy baseline.

cost associated with policy implementation borne by households to reduce a ton of CO_2 emissions. Table 8 shows that the fuel tax and the registration tax burden an average household in the lowest-income class with approximately 97,000 JPY and 170,000 JPY to reduce a ton of CO_2, respectively. It is notable that the shadow cost of the fuel tax is more than four times higher than the value of the current fuel tax rate in Japan of 21,603 JPY/ton of CO_2. This is because the fuel tax causes households not only to suppress their demand for travel but also to forgo the purchase of cars, thus the real tax burden is higher than the nominal value. Table 8 also shows that the registration tax imposes additionally 1.7 times more tax burden on all income classes than the fuel tax. In addition, it is evident that the shadow costs of the two taxes are higher for low-income classes. This is because low-income households tend to own fuel-efficient vehicles and drive short distances ahead of the imposition of taxes, so their potential for the additional abatement of a ton of CO_2 emissions is not significant compared with high-income households.

The second and fourth columns of Table 8 present the changes in consumer surplus as a percentage of household income, and based on these figures, Figure 3 compares the degree of the regressivity between the two taxes. Following Suits (1977), I construct the Lorenz curve in Figure 3 by plotting the cumulative share of total income horizontally and the cumulative share of total tax burden measured in loss of consumer welfare vertically, with households being sorted in the order of their incomes. The diagonal line (solid line) corresponds to the situation where households in all income groups incur the tax burden evenly. I find that the Lorenz curves for the fuel tax and the registration tax are located above the diagonal line and the former places closer to the diagonal line than the latter, suggesting that both the two taxes are regressive, but the degree of regressivity is less intense for the fuel tax than the registration tax. This result is consistent with that obtained by West (2004), who shows that gasoline or miles taxes are less regressive than a product tax, such as a tax on engine size, in the United States.[31]

6.4 Decomposition of CO_2 Emissions

I conduct a decomposition analysis to shed light on the sources of environmental externalities arising under each policy scenario. Through the decomposition analysis, it is evident which factor contributes to the change in CO_2 emissions and particularly the extent to which the rebound effect estimated in the previous section affects the increase in the externality.

Following D'Haultfœuille et al. (2014), I define some potential variables for the decomposition analysis. Let $d \in \{0, 1\}$ denote a policy indicator that equals zero before policy introduction (a policy status that corresponds to the baseline scenario) and one after policy introduction. Denoting $\mathrm{CO}_{2,t}(d)$ as the potential total CO_2 emissions arising from driving cars purchased in year t with policy status d, the variation in CO_2 emissions in year t due to the introduction of a policy Δ_t is written as

$$\Delta_t = \mathrm{CO}_{2,t}(1) - \mathrm{CO}_{2,t}(0),$$

where

$$\mathrm{CO}_{2,t}(d) = \int\int \sum_{j=1}^{J_t} e_{jt} M_{ijt}(d) N_t s_{ijt}(d)\, dF(D_i)\, dG(v_i).$$

In the expression, $M_{ijt}(d)$ is the annual distance traveled by car j purchased by household i in year t with policy status d, and $s_{ijt}(d) = s_{ijt}(r_t(d))$ is a choice probability evaluated at equilibrium rental prices r_t. In what follows, to control for the influence of vehicle attributes other than e_{jt} on CO_2 emissions, I separate vehicles into K groups of $\{\mathcal{J}_1, \ldots, \mathcal{J}_K\}$ based on vehicle attributes x_{jt} and calculate Δ_t by summing the changes in CO_2 emissions by group.[32]

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[31] Previous studies have found that a fuel tax is at least less regressive than a product tax. For example, Xiao and Ju (2014) show that the degree of regressivity of a fuel tax is almost identical with a consumption tax based on displacement in China.

[32] In practice, I form 100 groups $\{\mathcal{J}_1, \ldots, \mathcal{J}_{100}\}$ based on vehicle attributes x_{jt}.

I decompose the change in emissions Δ_t into the following four components:

$$\Delta_t = \sum_{k=1}^{K} \int\int \Bigg[\underbrace{Q_{k,it}(0) \sum_{j \in \mathcal{J}_k} (e_{jt} - \bar{e}_{k,t}) M_{ijt}(1) \Delta s_{ijt}^{inside}}_{\text{Composition effect}} + \underbrace{Q_{k,it}(0) \bar{e}_{k,t} \sum_{j \in \mathcal{J}_k} (M_{ijt}(1) - \bar{M}_{k,it}(1)) \Delta s_{ijt}^{inside}}_{\text{Rebound effect}}$$

$$+ \underbrace{N_t \sum_{j \in \mathcal{J}_k} e_{jt} (\Delta M_{ijt}) s_{ijt}(0)}_{\text{Fuel cost effect}} + \underbrace{N_t \left(\sum_{j \in \mathcal{J}_k} e_{jt} M_{ijt}(1) s_{ijt}^{inside}(1) \right) \sum_{j \in \mathcal{J}_k} \Delta s_{ijt}}_{\text{Fleet size effect}} \Bigg] dF(D_i)\, dG(v_i),$$

where

$$Q_{k,it}(0) = N_t \sum_{j \in \mathcal{J}_k} s_{ijt}(0), \quad s_{ijt}^{inside}(d) = \frac{s_{ijt}(d)}{\sum_{j \in \mathcal{J}_k} s_{ijt}(d)}, \text{ and}$$

$$\Delta V = V(1) - V(0), \; V \in \{M_{ijt}, s_{ijt}, s_{ijt}^{inside}\}.$$

Additionally, $\bar{e}_{k,t}$ and $\bar{M}_{k,it}(d)$ represent the average CO_2 emissions per kilometer e_{jt} and the average travel distance $M_{ijt}(d)$ in group k, respectively. The first term in the above expression refers to a fleet composition effect, which captures an expected decrease in emissions caused by the change in the sales mix. A fuel tax or a purchase incentive is expected to reduce emissions through the composition effect by promoting the shift in sales toward fuel-efficient vehicles. As such, the composition effect will be negative when these policies are introduced. The second term refers to the rebound effect, which represents an expected increase in emissions due to the increased driving distance when a household changes its car choice depending on policy status d. In the equation, this effect is captured by a correlation between driving distance $M_{ijt}(1)$ and the change in market share within the inside options Δs_{ijt}^{inside}. The third term is called the fuel cost effect, which captures the direct effect of the change in the fuel cost on driving distance. Since the imposition of a fuel tax raises per-kilometer cost of driving and decrease driving distance, the fuel cost effect will be negative. On the other hand, since a purchase incentive does not affect the fuel cost as far as a household chooses the same car in either policy status $d = 0, 1$, the fuel cost effect comes to zero. Finally, the fourth effect, the fleet size effect, captures the change in CO_2 emissions arising from a change in the number of cars owned by households due to the introduction of a policy. The fleet size effect here is obtained by the expected CO_2 emissions arising from driving a car multiplied by the change in the sales of automobiles.

Table 9 shows the results of the decomposition analysis.[33] The table reports changes in CO_2 emissions from the no-policy baseline scenario and the contribution ratios of the four effects. As

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[33] Note that the decomposition analysis targets at new vehicles purchased in a given year. Therefore, the estimates of the fuel cost effect and the fleet size effect reported in Table 9 will change when taking into account the effects on vehicles already owned by households who chose the outside option in that year. I believe that the fuel cost effect will become larger when considering the effect of the fuel tax on the driving distance of vehicles already owned, and the

Table 9: CO_2 Decomposition

	Fuel tax		Actual purchase incentive	
	Δ_t (kilotons of CO_2)	(%)	Δ_t (kilotons of CO_2)	(%)
Total	-697.2	-100.0	654.6	100.0
Composition effect	-12.6	-1.8	-43.1	-6.6
Rebound effect	1.5	0.2	2.9	0.4
Fuel cost effect	-118.3	-17.0	0.0	0.0
Fleet size effect	-567.8	-81.4	694.9	106.1

Note: This table reports the changes in CO_2 emissions from the no-policy baseline, Δ_t, and the contribution rates of the four effects calculated using the 2012 sample. The rate of the fuel tax in the first column is set at the current tax rate of 21,603 JPY/ton of CO_2.

expected, the composition effect contributes to reductions in the CO_2 emissions in the fuel tax and actual purchase incentive scenarios since each policy introduction changes the fleet composition and shifts sales toward fuel-efficient cars. While both the policy scenarios improve the average fuel economy of purchased vehicles, they generate the rebound effect that contributes to the increase in emissions. In particular, it turns out that the rebound effect induced by the purchase incentive cancels out approximately 7% of the emissions reduction resulting from the composition effect. In contrast, the fuel tax succeeds in controlling the rebound effect. Table 9 confirms that the fuel tax gives rise to the fuel cost effect, which totally offsets the emissions increase due to the rebound effect. Table 9 also suggests that the reduction in CO_2 emissions in the fuel tax scenario is driven primarily by the fuel cost effect and the fleet size effect.

7 Discussion and Conclusions

This study examines the efficiency and distributional equity of the purchase incentive and the fuel tax in Japan. To answer the empirical questions posed in the introduction, I evaluate the performance of purchase incentive as a green economic stimulus program and compare the regressivity of the two policies using a model with two decisions—on car ownership and utilization—on the demand side. I consider the identification of model parameters by combining microdata which come from a household survey and aggregate market data. To obtain consistent estimates of model parameters while addressing the car price endogeneity problem associated with demand estimation, I employ a maximum likelihood estimation with market share constraint.

The results obtained in my study have the following two implications. The first implication

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fleet size effect will decrease when a policy introduction encourages the replacement of old fuel-inefficient vehicles to new fuel-efficient vehicles. For these reasons, I focus only on the estimates of the composition effect and the rebound effect below.

highlights the importance of accounting for the rebound effect in evaluating energy efficiency programs. Prior studies that investigated how much energy efficiency programs contribute to energy use reduction have found that realized energy savings were significantly lower than those projected by ex ante engineering analyses (e.g., Davis et al., 2014; Levinson, 2016; Fowlie et al., 2018). I consider the rebound effect as a possible cause leading to such a gap between actual and anticipated energy use in the context of the purchase incentive for automobiles in Japan. Through a decomposition analysis, I find that the rebound effect induced by the purchase incentive cancels out approximately 7% of CO_2 emissions reduction that would have been attained by the improvement in vehicles' fuel economy. The result suggests that ignoring individual's behavioral changes after the implementation of energy efficiency programs such as a rebound effect would significantly overestimate their energy reduction effect. In addition, counterfactual analyses show that the purchase incentive considerably augments environmental externalities while stimulating demand, suggesting that the purchase incentive alone fails to simultaneously achieve two policies goals in terms of economy and environment (Tinbergen, 1952).

The second implication relates to the efficiency and distributional equity of a fuel tax and an annual registration tax. The simulation reveals that the fuel tax at the current tax rate in Japan is less costly and less regressive than the externality-equivalent registration tax proportional to vehicle's CO_2 emissions. There is an ongoing discussion toward the reform of automobile-related taxes in Japan. The results of my work suggest that social welfare could be improved without relatively increasing the tax burden on low-income households by substituting the existing registration taxes, such as the tonnage tax and the automobile tax, for carbon or fuel taxes in Japan.

I acknowledge some limitations to this study. The first limitation concerns the interpretation of the implications for the welfare effect of the purchase incentive. The analysis of this work concludes that the Japanese purchase incentive significantly improves social welfare. However, a separate discussion is needed to determine whether the government intervention by tax reductions or subsidies is an optimal policy option in a market with relatively high price-cost margin, even if such a market intervention is welfare-improving. Additionally, I account for CO_2 emissions only as an environmental externality from car use in assessing welfare impacts, but it should be noted that when considering other externalities, such as traffic accidents, congestion, local pollutants, and damage to the road, the total surplus of the purchase incentive may become smaller than that obtained in the analysis.

The second concern is regarding the regressive nature of the fuel tax and the annual registration tax. I rely on a static model to estimate the magnitude of the real tax burden on an annual basis based on welfare losses incurred due to each tax. Therefore, if the two taxes do not differently affect the duration of vehicle ownership, the conclusion drawn from the analysis would hold throughout the entire ownership period. Investigating the impact of tax impositions on the duration of vehicle ownership requires to estimate a dynamic model with detailed panel data, which goes beyond the scope of this study. I would like to make this aspect the subject of future research.

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A Appendix

A.1 Institutional Background of the Japanese Purchase Incentive

A.1.1 Automobile-Related Taxes

In this section, I outline automobile-related taxes in Japan. During the study period between 2006 and 2013, new car purchasers were obliged at the time of purchase to pay three types of automobile-related taxes: the acquisition tax, the motor vehicle tonnage tax, and the automobile tax.[34] Denoting the vector of the three automobile-related taxes as T_{jt}, the tax-inclusive price p_{jt} faced by a purchaser of car j in year t is expressed as follows:

$$\begin{aligned} p_{jt} &= p^e_{jt} + p\left(p^e_{jt}, T_{jt}\right) \\ &= \left(1 + \tau^{ex}\right) p^e_{jt} + T^{acq}_{jt} + T^{tonnage}_{jt} + T^{auto}_{jt}, \end{aligned}$$

where τ^{ex} represents the excise tax rate of 5%. The amount of the acquisition tax T^{acq}_{jt} is proportional to the acquisition price of the purchased car.[35] Thus, the sum of the rates of excise tax and acquisition tax yields the ad valorem tax rate. The acquisition tax rates are 5% for ordinary passenger cars and 3% for mini-vehicles.[36] On the other hand, the amounts of the tonnage tax $T^{tonnage}_{jt}$ and automobile tax T^{auto}_{jt} are proportional to the curb weight and engine displacement, respectively. For example, until March 2010, the tonnage tax amount was determined by a tax rate of 6,300 JPY (4,400 JPY) per 0.5 tonnes for ordinary passenger cars (for mini-vehicles).[37] The amount of the automobile tax is shown in Table A.1.

A.1.2 Purchase Incentive

The Japanese purchase incentive scheme is a rebate program, consisting of tax incentive measures and a subsidy program for fuel-efficient vehicles. Under the Japanese purchase incentive, the tax-inclusive vehicle price p_{jt} depends on the tax reduction rate tr_{jt} due to the tax incentive measures

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[34] While the acquisition tax involves a duty to pay only at the time of purchase, the tonnage tax and the automobile tax (or mini-vehicle tax for mini-vehicles) are payable by the owners every year after purchase. When an individual buys a new car, the first inspection is due three years after purchase. Thereafter, the vehicle must be inspected every two years. Regarding the tonnage tax, the amount of tax due each year is paid at the time of the vehicle inspection. Therefore, in practice, the purchaser of a new vehicle is obligated at the time of purchase to pay the tonnage tax for the three years until the next vehicle inspection.

[35] In practice, the acquisition price is approximately 90% of the tax-exclusive price p^e_{jt}. I note that the acquisition tax is not imposed on vehicles with the acquisition price less than 500,000 JPY.

[36] When the excise tax was raised to 8% in April 2014, the acquisition tax rate became 3% for ordinary passenger cars and 2% for mini-vehicles. The acquisition tax was abolished when the excise tax was raised to 10% on September 30, 2019.

[37] The tonnage tax rate was revised twice during the study period: 5,000 JPY (3,800 JPY) from April 2010 to April 2012 and 4,100 JPY (3,300 JPY) from May 2012 was added for every 0.5 tonnes for ordinary passenger cars (mini-vehicles).

and the amount of subsidy ES_{jt}. As I explain below, the tax reduction rate and the subsidy amount are determined according to fuel economy standards and emission standards.

Tax Incentive Measures Table A.2 shows the eligibility requirements for the tax incentive measures and the tax reduction rates tr_{jt} (or the deductible amounts) for target taxes during the sample period. As shown in Table A.2, the reduction rates for three automobile-related taxes are determined according to the achievement rates for the fuel economy standards and the emission standards.[38] For example, for purchasers of a new car meeting the 2010 fuel economy standard by 20% or more during the period between 2007 and 2008, the acquisition tax was reduced by 300,000 JPY (in the case of hybrid vehicles, the tax was cut by 2.0% in 2007 and 1.8% in 2008), and the automobile tax was cut by 50%.[39] In 2009, the system of the tax incentive measures were changed and substantially expanded as part of the Green New Deal programs. Table A.2 shows that, in the period 2009–2011, hybrid vehicles were exempt from their acquisition tax and tonnage tax regardless of their fuel economy achievement level.

Subsidy Program In addition to the tax incentives, a subsidy program for fuel-efficient cars has been implemented since 2009. During the sample period, the subsidy program had two phases. The first and second terms ran from April 2009 to September 2010 and from January 2012 to September 2012. During the first term, purchasers of a car achieving the 2010 fuel economy standard by 15% or more received a subsidy ES_{jt} of 100,000 JPY (50,000 JPY for mini-vehicles), and in the second term, purchasers of a car achieving the 2010 fuel economy standard by 25% or more or achieving the 2015 fuel economy standard received a subsidy of 100,000 JPY (70,000 JPY for mini-vehicles).

A.2 Derivation of the Direct Utility Function

I derive the direct utility function under the indirect utility specified in this paper. By solving the following optimization problem, I can obtain the direct utility function for household i conditional on purchasing car j in year t (Varian, 1992):

$$\begin{aligned} \min_{p^M_{jt}, p^X_t} \quad & \alpha_i \left(\frac{y_i - r_{jt}}{p^X_t} \right) + \lambda \exp \left(x'_{jt}\beta + h'_i\gamma - \rho_i \frac{p^M_{jt}}{p^X_t} \right) + w'_{jt}\psi + \xi_{jt} + \varepsilon_{ijt} \\ \text{subject to} \quad & p^M_{jt} M_{ijt} + p^X_t X_{it} = y_i - r_{jt} \end{aligned}$$

Note that the price of the Hicksian composite good p^X_t explicitly appears in the functions, although p^X_t is set to one by the normalization in the main body of this paper. The Lagrange function with

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[38] See Table A.3 for the target values of the fuel economy standards.

[39] The tax incentives implemented until 2008 were intended to reduce the acquisition tax and the automobile tax (or the mini-vehicle tax) for low-emission vehicles, comprising the following three schemes: the green tax scheme, the special scheme for fuel-efficient vehicles, and the acquisition tax incentive for clean-energy vehicles.

its multiplier μ takes the following form:

$$\mathcal{L} = \alpha_i \left(\frac{y_i - r_{jt}}{p_t^X} \right) + \lambda \exp \left(x'_{jt}\beta + h'_i\gamma - \rho_i \frac{p_{jt}^M}{p_t^X} \right) + w'_{jt}\psi + \xi_{jt} + \varepsilon_{ijt} - \mu \left(y_i - r_{jt} - p_{jt}^M M_{ijt} - p_t^X X_{it} \right).$$

Then, the optimization problem yields the first-order conditions:

$$\begin{aligned}
&- \frac{\lambda\rho_i}{p_t^X} \exp \left(x'_{jt}\beta + h'_i\gamma - \rho_i \frac{p_{jt}^M}{p_t^X} \right) + \mu M_{ijt} = 0 \\
&- \frac{\alpha_i(y_i - r_{jt})}{\left(p_t^X\right)^2} + \frac{\lambda\rho_i p_{jt}^M}{\left(p_t^X\right)^2} \exp \left(x'_{jt}\beta + h'_i\gamma - \rho_i \frac{p_{jt}^M}{p_t^X} \right) + \mu X_{it} = 0 \\
&p_{jt}^M M_{ijt} + p_t^X X_{it} = y_i - r_{jt}
\end{aligned}$$

Arranging these conditions, I have the direct utility function as follows:

$$\alpha_i X_{it} + \left\{ 1 + \log \left(\frac{\lambda\rho_i}{\alpha_i} \right) + x'_{jt}\beta + h'_i\gamma - \log M_{ijt} \right\} \frac{\alpha_i M_{ijt}}{\rho_i} + w'_{jt}\psi + \xi_{jt} + \varepsilon_{ijt}.$$

Note here that the second term in the expression is proven to be concave in driving demand M_{ijt}.

A.3 Computation of Equilibrium Prices

In this section, I describe the computation of equilibrium prices by the method of Morrow and Skerlos (2011). First, I divide the Jacobian matrix $\partial s_t(r_t)/\partial r_t$ into the following two matrices:

$$\frac{\partial s_t(r_t)}{\partial r_t} = \Lambda_t - \Gamma_t$$

where Λ_t is a $J_t \times J_t$ diagonal matrix and Γ_t is a $J_t \times J_t$ matrix with the following elements:

$$\Lambda_{jj,t} = \int\int (-\alpha_i) s_{ijt} \, dF(D_i) \, dG(v_i), \quad \Gamma_{jk,t} = \int\int (-\alpha_i) s_{ijt} s_{ikt} \, dF(D_i) \, dG(v_i).$$

Substituting these matrices into the pricing equations defined in (3.5), I have the following:

$$p_t^e = \widehat{mc}_t + \zeta_t, \quad \text{where} \ \ \zeta_t = \Lambda_t^{-1}(\Gamma_t \odot \Omega_t^*)(p_t^e - \widehat{mc}_t) - \Lambda_t^{-1} s_t^e(r_t). \tag{A.1}$$

Then, I iterate function $\widehat{mc}_t + \zeta_t \mapsto p_t^e$ until $\|\Lambda_t(p_t^e - \widehat{mc}_t - \zeta_t)\|_\infty < \epsilon^{tol}$ is satisfied and define the convergence points as the new equilibrium prices.

Derivation of Equation (A.1) Replacing the marginal costs mc_t in (3.5) with the estimates $\widehat{mc}_t$ yields

$$p_t^e = \widehat{mc}_t + \Omega_t^{-1} s_t^e(r_t).$$

Then, I transform the second term by following matrix algebra and obtain the desired result.

$$
\begin{aligned}
p_t^e &= \widehat{mc}_t + (S_t \odot \Omega_t^*)^{-1} s_t^e(r_t) \\
&= \widehat{mc}_t + (-\Lambda_t + \Gamma_t \odot \Omega_t^*)^{-1} s_t^e(r_t) \\
&= \widehat{mc}_t + \left[-\Lambda_t^{-1} + \Lambda_t^{-1}(\Gamma_t \odot \Omega_t^*) \left\{ E - \Lambda_t^{-1}(\Gamma_t \odot \Omega_t^*) \right\}^{-1} (-\Lambda_t)^{-1} \right] s_t^e(r_t) \\
&= \widehat{mc}_t - \Lambda_t^{-1} s_t^e(r_t) + \Lambda_t^{-1}(\Gamma_t \odot \Omega_t^*) \left[-\Lambda_t \left\{ E - \Lambda_t^{-1}(\Gamma_t \odot \Omega_t^*) \right\} \right]^{-1} s_t^e(r_t) \\
&= \widehat{mc}_t - \Lambda_t^{-1} s_t^e(r_t) + \Lambda_t^{-1}(\Gamma_t \odot \Omega_t^*)(p_t^e - \widehat{mc}_t),
\end{aligned}
$$

where E denotes an identity matrix. In the transformation above, note that $\Lambda_t \odot \Omega_t^* = \Lambda_t$ as Λ_t is a diagonal matrix and the diagonal elements of the ownership matrix Ω_t^* are all ones. Additionally, I apply the Woodbury formula to obtain the third equation.

A.4 Additional Figures and Tables

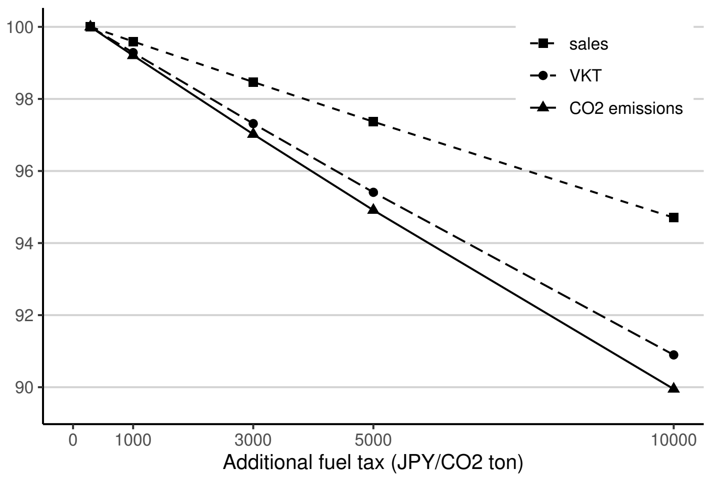

Figure A.1: Impacts of Additional Fuel Taxes on Sales, VKT, and CO_2 emissions

Note: The graphs show the changes in the total sales, the aggregate VKT, and the total CO_2 emissions from driving cars purchased in 2012 when fuel taxes of 1,000, 3,000, 5,000, and 10,000 JPY/ton of CO_2 are added to the current tax rate of 21,603 JPY/ton of CO_2.

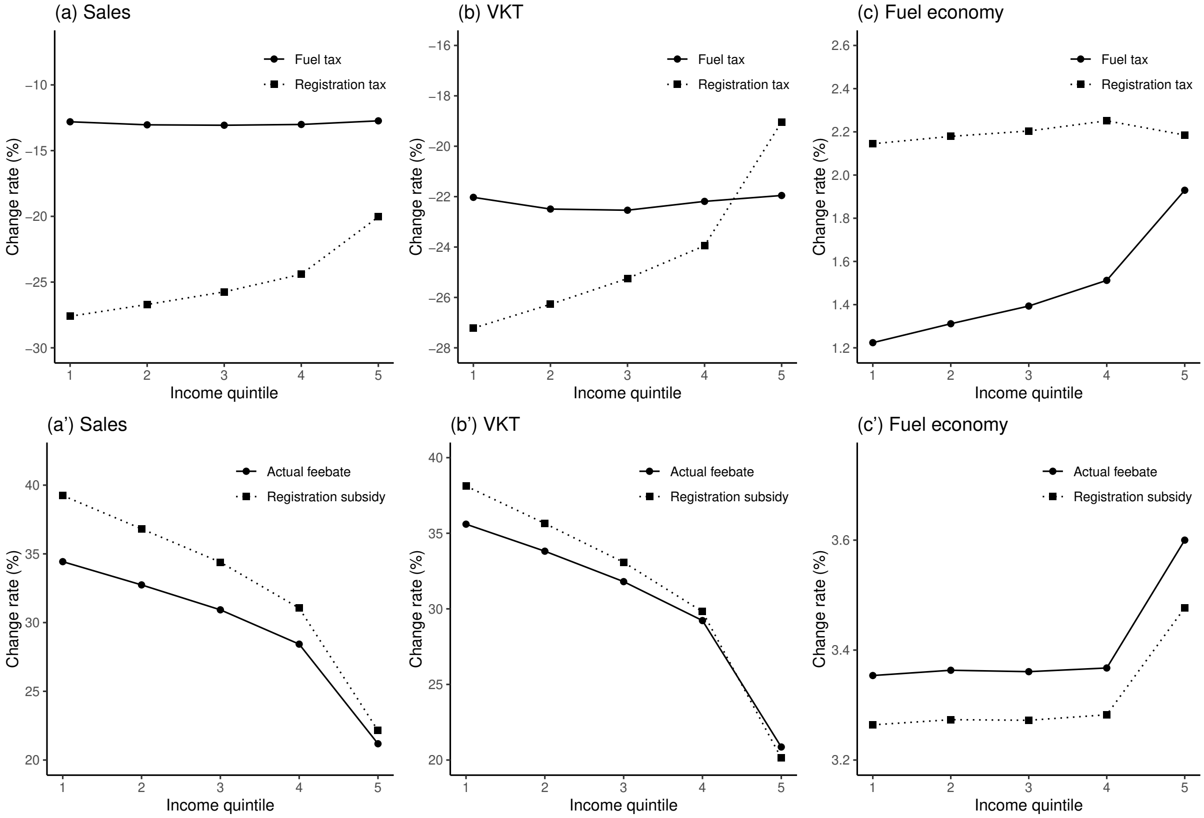

Figure A.2: Policy Impacts on Various Outcomes by Income Quintile

Note: The graphs display the policy impacts on the total sales, aggregate VKT, and sales-weighted average of fuel economy of vehicles purchased in 2012 by income quintile from 1 (lowest) to 5 (highest), with the impacts of the fuel tax at the current tax rate and the externality-equivalent registration tax on the top and those of the actual purchase incentive and the externality-equivalent registration subsidy on the bottom. The vertical axes represent the rates of change in variables when each policy is introduced into the no-policy baseline scenario.

Table A.1: Automobile Tax Amounts

displacement (L)	tax amount (JPY)	displacement (L)	tax amount (JPY)
<1.0	29,500	3.5-4.0	66,500
1.0-1.5	34,500	4.0-4.5	76,500
1.5-2.0	39,500	4.5-6.0	88,000
2.0-2.5	45,000	>6.0	111,000
2.5-3.0	51,000	Kei car	7,200
3.0-3.5	58,000		

Table A.2: Eligibility Requirements for the Tax Incentive Measures (2006–2013)

Requirements	Acquisition tax	Tonnage tax	Automobile tax
Panel A. Year 2006			
2010 FE target values +10% and ES 4 stars	150,000 JPY (2.2%)	-	25%
2010 FE target values +20% and ES 4 stars	300,000 JPY (2.2%)	-	50%
Panel B. Years 2007–2008			
2010 FE target values +10% and ES 4 stars	150,000 JPY	-	25%
2010 FE target values +20% and ES 4 stars	300,000 JPY (2.0%, 1.8%)	-	50%
Panel C. Years 2009–2011			
2010 FE target values +15% and ES 4 stars	50% (100%)	50% (100%)	25%
2010 FE target values +25% and ES 4 stars	75% (100%)	75% (100%)	50%
Panel D. Years 2012–2013			
2015 FE target values and ES 4 stars	50%	50%	25%
2015 FE target values +10% and ES 4 stars	75%	75%	50%
2015 FE target values +20% and ES 4 stars	100%	100%	50%

Source: JAMA (2006; 2007; 2008; 2009; 2012).

Note: The table presents the eligibility requirements for the tax incentive measures from 2006 to 2013. The 2010 (2015) FE target values refer to the 2010 (2015) fuel economy target values, and the ES 4 stars represent the emission-standard four stars, awarded to vehicles whose emission values represent a reduction of at least 75% from the 2005 regulatory levels. The monetary amounts represent what is deductible from the purchase price, and figures in percentage terms represent the reduction rates for automobile-related taxes. The tax reduction rates for hybrid vehicles are reported in parentheses. The light vehicle tax was not targeted by the tax incentive measures between 2009 and 2013.

Table A.3: Fuel Economy Standards

2010 Standard		2015 Standard			
curb weight (kg)	target value (km/L)	curb weight (kg)	target value (km/L)	curb weight (kg)	target value (km/L)
<703	21.2	<601	22.5	1531-1651	13.2
703-828	18.8	601-741	21.8	1651-1761	12.2
828-1016	17.9	741-856	21.0	1761-1871	11.1
1016-1266	16.0	856-971	20.8	1871-1991	10.2
1266-1516	13.0	971-1081	20.5	1991-2101	9.4
1516-1766	10.5	1081-1196	18.7	2101-2271	8.7
1766-2016	8.9	1196-1311	17.2	>2271	7.4
2016-2266	7.8	1311-1421	15.8		
>2266	6.4	1421-1531	14.4		

Note: This table shows the target values for the 2010 and 2015 fuel economy standards. Fuel economy standards have been revised many times since they were first established in 1979. For ordinary passenger cars, the 2010 and 2015 target values were established in March 1999 and in March 2006, respectively. The 2010 target values were used in the first term and the 2015 target values in the second term to select vehicles for tax reduction.