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Welfare Effects of Fuel Tax and Feebate Policies in the Japanese New Car Market

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Abstract

This paper examines the efficiency and distributional effects of fuel tax and feebate policies in the automobile market. I employ a model in which households make two-stage decisions on car ownership and utilization, and I estimate model parameters by combining micro-level data from a household survey and macro-level aggregate data on the Japanese new car market from 2006 through 2013. Interestingly, several system changes in the Japanese feebate created rich variations in vehicle prices across vehicles and over time during the sample period. I use such exogenous variation to overcome the vehicle price endogeneity associated with demand estimation. Counterfactual analyses show that the Japanese feebate results in a significant increase in social welfare while augmenting environmental externalities. In particular, the rebound effect induced by the feebate cancels out approximately 7% of the reduction in CO_2 emissions that would originally have been attained by the improvement in fuel economy. In addition, I find that the fuel tax at the current tax rate in Japan is 1.7 times less costly than the product tax, an alternative feebate scheme considered in the counterfactuals. I also find that there is no difference in regressivity between the two policies in reducing negative environmental externalities by the same amount.

Keywords: Discrete-Continuous choice, Fuel tax, Feebate policy, Rebound effect, Decomposition, Distributional impact
JEL Codes: D12, H23, L62, Q53

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1 Introduction

Reducing fuel consumption from car driving is an urgent challenge common to most countries. Among the policy instruments for resolving this challenge, feebate policies have gained popularity. Feebate policies provide price incentives for automobiles depending on fuel efficiency to encourage households to replace old fuel-inefficient vehicles with new fuel-efficient vehicles. When facing the financial crisis in 2008, a growing number of countries adopted green economic stimulus programs such as feebates with the aim of combatting the economic recession and climate change. On the other hand, while policymakers would agree that a carbon tax is an effective policy instrument for reducing environmental externalities from car driving, they tend to avoid raising a fuel tax or introducing a carbon tax for several reasons. The foremost reason is that policymakers have concerns about the distributional impacts of taxes on fuel. Hence, this study attempts to empirically answer the following questions: Can we simultaneously achieve these economic and environmental goals with feebate policies? Is a fuel tax more regressive than a comparable feebate?

In this paper, I evaluate the welfare effects of a fuel tax and a feebate policy, focusing on efficiency and distributional equity. In particular, the interest of this paper is in examining the impacts of the two policies on multiple stages of households' decisions. This has important implications for assessing the welfare effects of policies, including their environmental impacts. For example, a fuel tax is expected to affect not only driving distances but also car choices by changing expected future fuel costs. Similarly, a feebate policy directly affects car choices by incentivizing individuals to purchase fuel-efficient vehicles, while it should presumably affect mileage choices by altering the attributes of cars purchased. Therefore, I resort to a structural model that incorporates decisions on the purchase and use of cars into its demand model for policy evaluation.

Moreover, the social outcomes of the two policies largely depend on a rebound effect. The rebound effect here refers to the upward pressure on driving demand that results from the improvement of fuel economy followed by a downward shift in the per-kilometer marginal cost of driving. Because of the rebound effect, policies that encourage improvements in fuel economy do not always result in the intended reduction of fuel consumption. Many researchers have empirically identified the existence of the rebound effect (e.g., Gillingham et al., 2016). Since a fuel tax directly suppresses driving demand by imposing a tax on marginal environmental externalities from car use, it can control upward pressure on driving demand spurred by the rebound effect. In addition, a fuel tax can be an efficient policy instrument because it equates marginal abatement costs incurred by individuals even when actual individual car usage varies. However, a feebate promotes the dissemination of fuel-efficient cars by providing tax incentives for their purchase; however, it fails to control driving demand after purchase. Thus, the feebate is expected to encourage households to drive more through the rebound effect (Anderson and Sallee, 2016).

To account for the rebound effect in evaluating policy impacts, I model two household decisions, one concerning which car to purchase and, thereafter, another regarding how far a household drives the car. Several studies have focused on two-stage decision-making; however, the number of studies has been limited due to issues of data availability. For instance, Goldberg (1998), West (2004), and Bento et al. (2009) model the two decisions to analyze the effects of fuel economy standards and a fuel tax using data from a large sample of households in the United States. Such analyses requires large-scale household-level data, including detailed information on the choice and usage of cars. However, in many cases, such micro-level data are not available, and this data limitation has hindered the analysis.

In this study, I attempt to overcome this problem by combining two data sets. The first data set comes from a household survey administered in 2013 to households in Japan who had purchased a passenger vehicle within the past five years. This survey provides detailed information on car ownership and utilization for each household, such as the car model, the year purchased, and the distance traveled. The survey also reports household demographics, such as household income, family size, and residential address. On the other hand, the second set of data comes from an aggregate data set on the Japanese new car market between 2006 and 2013. This aggregate market data set contains information on sales volume, price, and other car attributes for each base model and covers nearly all models in the Japanese new car market. Importantly, the combination of the data sets at the different levels helps construct choice sets faced by surveyed households in each market. I match the micro-level information from the household survey and the macro-level information from the aggregate data set by using a model name common across the two data sets.

I focus on Japanese regulations in the automobile market for several reasons. First, during the 2006–2013 sample period, the Japanese feebate policy experienced multiple system changes. Importantly, the system changes expanded the monetary amounts and coverage of the feebate, leading to variations in vehicle prices across vehicles and over time. These exogenous variations are crucial to identifying model parameters. The second is attributed that the Japanese feebate policy being an attribute-based regulation (Ito and Sallee, 2018). Under the scheme, the amounts of the rebate are determined according to vehicle weight and displacement as well as vehicle fuel economy. Regarding this point, some offer the critique that the Japanese feebate provides more subsidies to heavy, fuel-inefficient vehicles rather than light, fuel-efficient vehicles. Hence, I conduct a counterfactual analysis to examine whether a change in the design of the scheme to address such criticisms improves social welfare. The third is related to the fact that a carbon tax was newly introduced during the sample period. In Japan, gasoline and diesel have long been subject to fuel taxes with high rates, with the gasoline tax representing approximately one-third of the gasoline price. In addition to the existing fuel taxes, a carbon tax was phased in 2012, the introduction of which led to exogenous variation in fuel prices. I use such variation to identify the responses of consumers and producers to fuel price changes.

I begin by constructing a model that describes the behaviors of households and firms in the automobile market. On the demand side, I model the household's behavior as a two-stage problem.

Specifically, I describe the joint demand for vehicle and use with the discrete-continuous choice (DCC) model following Bento et al. (2009). On the supply side, I model the pricing strategies of car manufacturers in an oligopolistic market, and following Berry et al. (henceforth BLP, 1995) and subsequent studies, I assume that differentiated, multiproduct firms determine their prices based on those of rival firms. The model in this study has two advantages. First, it allows me to drop the restrictive assumption made in most previous studies that driving demand is completely inelastic with respect to operating costs; I thus evaluate the policy effects without making any assumptions concerning the elasticity of driving demand. Second, by following the estimation strategy proposed by BLP (1995), I address the car price endogeneity associated with demand estimation based on aggregate market data. In particular, I identify parameters of the DCC model using micro-level and macro-level moment conditions and estimate the parameters with the maximum likelihood estimation (MLE), following Goolsbee and Petrin (2004) and Train and Winston (2007).

Moreover, I account for the heterogeneity of the rebound effect across individuals in the model. Existing empirical studies find that since actual car usage patterns differ considerably between urban and rural areas, the magnitude of the rebound effect varies across regions even within the same country (e.g., Gillingham, 2014). I present evidence of the heterogeneity of the rebound effect by performing a preliminary analysis before the structural estimation. The simple regression analysis suggests the possibility of a large interregional disparity in the rebound effect over the sample period in Japan. I attempt to capture this heterogeneity by introducing a random coefficient into the structural model. The micro-level data used in this study help to identify the heterogeneity.

I make several findings associated with the rebound effect. First, the empirical result indicates the existence of the rebound effect and its heterogeneity across individuals. I estimate a rebound effect of 0.09%, which means that a 1% decrease in the cost of driving leads to an increase in driving demand of 0.09%. In addition, I find that the rebound effect is heterogeneous across individuals, with spreading over an interquartile range of 0.07–0.11%. Second, the result from the structural estimation demonstrates the importance of considering household decisions regarding the choice and use of cars. As a result of a simple regression that focuses only on the relationship between driving demand and the cost of driving, I find that, compared to the result from the structural estimation, the OLS result significantly overestimates the rebound effect. This suggests that it is crucial to model the two endogenous household decisions.

I perform several counterfactuals and quantify welfare effects of policies with four different measures of surplus: consumer surplus, producer surplus, tax revenues, and environmental externalities. There are two primary findings from the simulation. First, I find that the Japanese feebate policies significantly stimulate demand for automobiles and result in an increase in social welfare while exacerbating environmental externalities. This increase in the negative externality is due to not only the increase in the number of cars purchased by households but also the rebound effect. In fact, a decomposition analysis reveals that the rebound effect induced by the feebate cancels out approximately 7% of the reduction in CO_2 emissions that would originally have been attained by the improvement in fuel economy. The results demonstrate that green economic stimulus policies such as the feebate fail to achieve both their economic and environmental goals.

In addition, the simulation results suggest that altering the feebate scheme design can improve consumer welfare, with the environmental externality being held unchanged. I find that, compared with the actual, attribute-based feebate scheme, an alternative feebate scheme that determines subsidy amounts based solely on vehicle fuel economy increases the consumer surplus of low-income households by subsidizing light, fuel-efficient vehicles. However, this change in scheme design reduces producer surplus and tax revenues because it decreases the sales of heavy, large-sized vehicles relative to the actual feebate.

Second, the simulation presents the cost-effectiveness of a fuel tax over a product tax, which is an alternative feebate scheme considered in the counterfactual analysis. Specifically, the fuel tax at the current tax rate in Japan is 1.7 times less costly than a product tax for reducing environmental externalities by the same amount. Furthermore, I find that there is no substantial difference in regressivity between the fuel tax and the product tax, although the latter is slightly more regressive than the former. The simulation analysis confirms that both policies are regressive until the fourth quintile income group and become progressive in the fifth quintile income group. Finally, my simulation analysis also provides some findings on elasticities associated with the carbon tax rate. In particular, I find that a 1% increase in the carbon tax in the future leads to a 0.22% decrease in Japanese CO_2 emissions.

This study contributes to two strands of the literature. First, this study relates to the literature that evaluates feebate policies in car markets. Several papers have studied the welfare impacts of feebate policies in car markets (see, e.g., Konishi and Zhao (2017) and Kitano (2016, 2022) for a study on the Japanese feebate and D'Haultfœuille et al. (2014) and Durrmeyer (2021) for a study on the French feebate). I contribute to the literature by examining the economic and environmental consequences of the Japanese feebate policy, while accounting for rebound effects and the equilibrium in the car market. Importantly, Tinbergen (1952) notes that achieving multiple policy targets requires more policies than the number of policy targets. In this study, I demonstrate Tinbergen's rule by indicating that the feebate stimulates demand while augmenting environmental damage.[1]

Second, this paper also contributes to the argument about the distributional effects of a fuel tax and a feebate policy. Seminal papers that analyze the distributional impacts of car market regulations are Bento et al. (2009) and Jacobsen (2013), who study the impacts of the fuel tax and the corporate average fuel economy standards in the United States. Recently, Davis and Knittel

[1] Li et al. (2021) analyze the impacts of the cash-for-clunkers program in the United States and find that the program failed to achieve its economic stimulus and environmental objectives, indicating that Tinbergen's (1952) rule does not hold. My work complements the results of Li et al. (2021) by evaluating the impacts of a feebate policy on households' choices of vehicle and miles traveled.

(2019) and Levinson (2019) also argue about the regressivity of these regulations. Regarding the feebate policy, Durrmeyer (2021) examines the distributional impacts of the French feebate. I analyze the impacts of the fuel tax and feebate policy on households with different incomes by employing a structural model. In particular, my contribution is to argue for the regressivity of the two policies in terms of consumer welfare when accounting for households' decisions on car choice and use.

The remainder of this paper is organized as follows. Section 2 describes the data sets and institutional background of the Japanese feebate policy 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

In this section, I first explain the data sets used in the analysis. I then outline the institutional background of the feebate scheme in Japan. In particular, I highlight exogenous variation in vehicle prices generated by several system changes of the Japanese feebate that is helpful for the identification of model parameters. Finally, I 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 is a household survey commissioned by the Nippon Research Center (NRC). This survey was conducted online in November 2013 and targeted households nationwide who had purchased passenger cars in the past five years. The survey provides 548 observations for this study. The household survey contains information on the model purchased, purchase year, total travel distance for each vehicle, and household demographics such as income, the 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. Using these market-level data enables me to construct the choice set faced by households in selecting a car. I obtain information 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. On the other hand, the information on the sales volumes of imported vehicles comes from statistics released by the Japan Automobile Importers Association (JAIA). The statistics include sales data on the top-20 best-selling imported vehicles sold in Japan for each year.[2] In addition to the sales data, 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 has 1,302 observations over eight years for each base model, with nine Japanese and seven overseas car manufacturers. I combine the household survey and aggregate data based on the model name common to both data sets.

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

Table 1 presents the summary statistics for variables used in the analysis. The first row in Panel A reports the annual vehicle kilometers traveled (VKT) for each vehicle owned by households.[3] The annual VKT is approximately 5,480km on average. This value is close to the average travel distance obtained from the nationwide survey of the Japan Automobile Manufacturers Association (JAMA).[4] In addition, I find that the household incomes are slightly higher than the national average because the NRC's survey only targets households who have purchased cars. 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. On the other hand, other demographics such as family size, the age of the household head, and the urban dummy take values close to the population averages, where the urban dummy indicates whether a household resides in ordinance-designated cities.

The variables in Panel B are defined as follows. The rental price represents the annual cost of vehicle ownership and is calculated based on the purchase price. Specifically, I construct the rental price as the sum of depreciation, repayment amount of car loan interest, and annualized automobile taxes in each year.[5] The automobile-related taxes shown in Panel B indicate the total tax amount

[2] In Japan, imported vehicles 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%.

[3] I define the annual VKT as the total travel distance divided by years of use.

[4] The JAMA conducts a market-trend survey of passenger vehicles of households nationwide every two years and reports an average monthly VKT of 380km for 2013 (JAMA, 2013). Therefore, a rough estimate of the annual VKT comes to 4,560km.

[5] The depreciation is calculated based on the legal durable years by vehicle types. 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. Note that the purchase price here includes the excise tax-inclusive price, an acquisition tax, and a subsidy amount in the presence of the feebate policy. 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.

Table 1: Summary Statistics

	Unit	Mean	St. 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 data, 2006-2013 ($N = 1,302$)					
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 data. The 1st Q. and 3rd Q. in the table stand for the first and third quantiles. The automobile-related taxes in Panel B indicate the lump-sum tax amount at the time of purchase before applying the tax cut under the feebate.

before applying the tax cut under the feebate.[6] Table 1 shows that the automobile-related taxes amount to approximately 8% of the purchase price on average in the absence of the feebate policy. 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 automatic transmission (AT) or continuously variable transmission (CVT).

2.2 Japanese Feebate Scheme

Here, I briefly describe the Japanese feebate scheme and show how several system changes produced variations in the vehicle prices consumers faced. The details of the scheme are provided in Appendix Section A.1.

[6] During the sample period, the automobile-related taxes are composed of the acquisition tax, the motor vehicle tonnage tax, and the automobile tax. See Appendix Section A.1.1 for details on the automobile-related taxes.

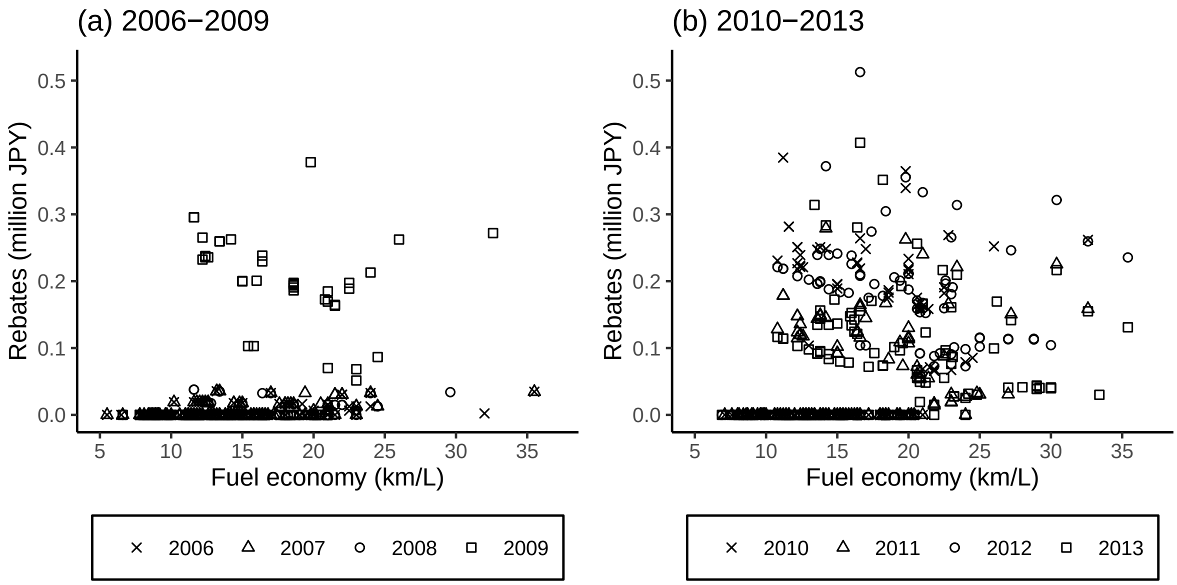

Figure 1: Variation in Rebates between 2006 and 2013

Note: The figure plots the amounts of rebates applied for each vehicle under the feebate policy during 2006–2009 (left figure) and 2010–2013 (right figure). The rebates here are defined as the sum of the tax cut and subsidy amounts.

The Japanese feebate scheme is essentially a rebate program, consisting of (i) the tax incentive measures for automobile-related taxes and (ii) the subsidy program for fuel-efficient vehicles.[7] During the sample period from 2006 to 2013, the tax incentive measures have four implementation periods: 2006, 2007–2008, April 2009–April 2012, and May 2012–2013.[8] Similarly, the subsidy program introduced in 2009 has two implementation periods of April 2009–September 2010 and January 2012–September 2012.[9] These imply that the tax incentive measures and the subsidy program changed three times and one time during the sample period, respectively.

In particular, the feebate scheme was substantially expanded as one of the Green New Deal programs in 2009. Figure 1 displays rebates, the sum of the tax cut and subsidy amounts, applied for each vehicle under the feebate by year. I first find that the system reform in 2009 substantially expanded both the amounts and coverage of the tax cut and subsidy. Importantly, several system reforms during the sample period generated cross-vehicle price variations and time-series price

[7] 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. For details of the cash-for-clunkers program, see Kitano (2022).

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

[9] 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.

variations within a given vehicle. Figure 1 demonstrates that the rebates vary substantially across years even within a given vehicle, ranging from 0 JPY to 0.5 million JPY. These multidimensional fluctuations in vehicle price that are exogenous to consumers are crucial for the identification of model parameters. I use the variations to construct instrumental variables, as explained in a later section.

In addition, Figure 1 shows that the amount of the rebate is determined not only by the fuel economy but also the vehicle weight. This is attributable to the fact that the Japanese feebate policy is an attribute-based regulation, as studied by Ito and Sallee (2018). Figure 1 shows that fuel-efficient vehicles do not necessarily enjoy a relatively higher rebate than less fuel-efficient vehicles. In fact, many vehicles receive more rebates than hybrid vehicles with a fuel economy of over 35 km/ℓ.

Since the data available in this study are annual, I divide the implementation periods of the tax incentives and subsidy programs after 2009 into the following two periods: the first period from 2009 to 2011 and the second period from 2012 to 2013. As discussed in later sections, even with such definitions, the results obtained in this study are 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 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:

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

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).[10]

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

[10] Abe et al. (2017) run 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: $\log(M_{ijt})$		
	Coefficients	(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: Heteroskedasticity-robust standard errors are in parentheses. In the estimation, 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.

Model 3, I find the national average of the rebound effect to be 0.24. This suggests that the driving distance increases by 0.24% when the operating cost declines by 1%. Moreover, the summary statistics for population density indicate 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 in urban areas.[11] 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 feebate policy while accounting for the rebound effect, it is critical

[11] 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 a interquartile range of 0.17–0.83.

to (i) incorporate two household decisions on car purchase and utilization into a structural model, and (ii) consider the heterogeneity of the rebound effect in designing the model. I explain the methodology in the next section.

3 Model

In this section, I construct a structural model of the new car market. I assume for the demand model that each household makes two decisions about car purchase and use. For the supply model, I assume differentiated, multiproduct firms that compete in an oligopolistic market in a Bertrand-Nash manner.

3.1 Demand

I first present the demand model and describe its specification. Following Goldberg (1998) and Bento et al. (2009), I construct 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 its 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 exist N_t potential households in the automobile market, which is divided by year t $(= 1, \ldots, T)$. I assume that household i $(= 1, \ldots, N_t)$ buys at most one car j $(= 1, \ldots, J_t)$ or an outside option $(j = 0)$ each year. I define the indirect utility U_{ijt} of household i conditional on purchasing car j or the outside option in year t as

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

where V_{ijt} is part of the indirect utility that depends on both observed and unobserved car attributes and observed household attributes. The indirect utility U_{ijt} includes an idiosyncratic shock ε_{ijt} in the last term. In the real world, even though all households with the same characteristics face the same product-choice set, they do not necessarily all make the same choice. The inclusion of the idiosyncratic shock ε_{ijt} allows me to explain this choice variation across households. I assume ε_{ijt} to be an independently and identically distributed stochastic variable that follows the type I extreme value distribution.

Each household decides which car to buy based on (3.1). Specifically, I assume that a household chooses the car with the highest conditional indirect utility. Given the model parameters, the conditional probability of household i in year t choosing car j or the outside option is written as

$$\frac{\exp(V_{ijt})}{\sum_{k=0}^{J_t} \exp(V_{ikt})}.$$

Given purchasing car j in year t, household i determines VKT M_{ijt} subject to the budget constraint,

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

In the budget constraint, p_{jt}^{M} denotes the per-kilometer cost of driving, which is defined as the gasoline price p_t^{gas} at the time of purchase divided by car j's fuel economy. The second term X_{it} expresses the Hicksian composite good consumption for household i, where the price of the composite good is normalized to one.[12] On the right-hand side, y_i denotes household i's income, and r_{jt} represents the rental price that is calculated based on the purchase price p_{jt}, so that $y_i - r_{jt}$ expresses the residual income after purchasing car j.

Here, I specify V_{ijt} in the indirect utility (3.1) as follows:[13]

$$V_{ijt} = \alpha_i \left(y_i - r_{jt} \right) + \lambda \exp\left(x_{jt}' \beta + h_i' \gamma - \rho_i p_{jt}^{M} \right) + w_{jt}' \psi + \xi_{jt} \tag{3.2}$$

In this specification, x_{jt} and w_{jt} each represent vectors of observed car attributes, and h_i represents a vector of household characteristics. As shown below, x_{jt} appears in both the car choice and usage equations, whereas w_{jt} appears only in the car choice equation. Note that the second term of (3.2) expresses the interaction term between the car and household attributes. Additionally, ξ_{jt} captures car attributes observed by households and firms but unobserved by researchers. As in BLP (1995), I assume the rental price r_{jt} to be endogenous because r_{jt} may correlate with unobserved car attributes ξ_{jt}. Indeed, several factors in ξ_{jt}, such as advertisements and the brand image of automobile firms, are expected to affect the rental price. Finally, I normalize the indirect utility from the outside option ($j = 0$) to $V_{i0t} = \alpha_i y_i$. Regarding a direct utility function assumed under the indirect utility specification above, see Appendix A.2.

The specification of V_{ijt} involves random coefficients. I specify coefficients α_i and ρ_i as

$$\alpha_i = \alpha_0 + \alpha_1 y_i + \sigma_\alpha v_{i\alpha}, \quad \rho_i = \exp\left(\rho + \sigma_\rho v_{i\rho} \right), \tag{3.3}$$

where $v_{i\alpha}$ and $v_{i\rho}$ are independently distributed standard normal. In the specification of α_i, α_0 represents a mean parameter when household income is zero, and σ_α represents a standard deviation parameter. As assumed in BLP (2004), I include household income y_i as a preference shifter in α_i to capture the heterogeneity of price elasticities of demand across households with different incomes. I expect that households with higher incomes are unlikely to respond to the vehicle price change so that the coefficient α_1 becomes negative. On the other hand, the coefficient ρ_i captures the heterogeneous impacts of the driving cost on households' preferences. Specifically, ρ and σ_ρ

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

[13] I do not consider the situation where households misperceive fuel costs when making vehicle choices. Several studies that have analyzed the degree of undervaluation of future fuel cost savings obtained by purchasing fuel-efficient cars find that there is little such undervaluation by households (see, e.g., Busse et al., 2013, Sallee et al., 2016, and Grigolon et al., 2018).

correspond to the mean and standard deviation parameters for the distribution of ρ_i, respectively. In specification (3.2), the remaining parameters λ, β, γ, and ψ are assumed to be constant.

Under specification (3.2), I derive the demand for distance traveled M_{ijt}. When household i purchases car j in year t, applying Roy's identity to the indirect utility yields the driving demand M_{ijt} as follows:[14]

$$\begin{aligned} \log(M_{ijt}) &= \log\left(-\frac{\partial V_{ijt}/\partial p^M_{jt}}{\partial V_{ijt}/\partial y_i}\right) \\ &= \log\left(\frac{\lambda\rho_i}{\alpha_i}\right) + x'_{jt}\beta + h'_i\gamma - \rho_i p^M_{jt}. \end{aligned} \tag{3.4}$$

3.2 Supply

Next, I consider the pricing strategies of car manufacturers. 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 denote a set of cars that firm f produces in year t as $\mathcal{J}_{ft}$. Firm f determines its prices to maximize variable profit defined as follows:

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

where p^e_{jt} 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. Additionally, mc_{jt} denotes the marginal cost, which is assumed to be constant in quantity.

For the profit maximization, the first-order condition to be satisfied by p^e_{jt} is written as

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

where τ^{ad}_{jt} represents an ad valorem tax. Note that in the derivation of the first-order conditions, the rental price r_{jt} is a function of the purchase price p_{jt}. I can rewrite these J_t first-order conditions for profit maximization in matrix form and 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 $\Omega^*_{jk,t}$,

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

[14] Note that the income y_i that appears in (3.3) is not structurally embedded in the indirect utility but in a reduced form way.

With these matrices, defining $J_t \times J_t$ matrix $\Omega_t = \Omega_t^* \odot S_t$, where operator $\odot$ denotes the element-wise Hadamard product, I obtain the $J_t \times 1$ vector of tax-exclusive prices p_t^e from the following expression:

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

In the expression, mc_t is a column vector of marginal costs, and $s_t^e(r_t)$ is a column vector with $s_{jt}(r_t)/\{(1+\tau_{jt}^{ad}) dr_{jt}/dp_{jt}\}$ as its jth element.

4 Estimation and Identification

I explain the estimation and identification strategies for the model parameters. The basic idea for the estimation is that I embed the estimation procedure of the DCC model in the framework of BLP (1995), following Goolsbee and Petrin (2004) and Train and Winston (2007). I attempt to identify the parameters with micro-level and macro-level moments and address price endogeneity when estimating the demand function. Based on the demand parameters and conditions for profit maximization, I recover the marginal costs faced by each firm in the production process.

4.1 Estimation Strategy

I first present the overview of the estimation strategy before describing the details. First, I divide the parameters in V_{ijt} into two parts and denote them by vectors θ_1 and θ_2:

$$V_{ijt} = \delta_{jt}(\theta_1) + \mu_{ijt}(\theta_2), \tag{4.1}$$

where $\delta_{jt}(\theta_1)$ and $\mu_{ijt}(\theta_2)$ represent a mean utility that is common to all households and the part of utility depending on household characteristics, respectively. Specifically, for $j = 1, \ldots, J_t$, vectors θ_1 and θ_2 are composed of

$$\theta_1 = (\alpha_0, \psi), \quad \theta_2 = (\alpha_1, \lambda, \beta, \gamma, \rho, \sigma_\alpha, \sigma_\rho),$$

and for the outside option ($j = 0$), both $\delta_{0t}(\theta_1)$ and $\mu_{i0t}(\theta_2)$ are zero by definition. Both of the parameter vectors are supposed to be estimated via MLE when household-level data are available. However, a likelihood function defined under this specification includes over 1,300 fixed effects $\{\delta_{jt}\}_{j,t}$, and it is unrealistic to conduct a nonlinear search over all these parameters using MLE. Then, the market aggregate data help reduce the number of parameters to be estimated in a nonlinear search. Specifically, Berry's inversion (Berry, 1994; BLP, 1995) based on market shares in the aggregate data set enables me to express the fixed effects $\{\delta_{jt}\}_{j,t}$ as a function of the θ_2 parameter only. Finally, using the estimates of θ_1 and θ_2 parameters, I recover the marginal costs in the supply model.

As the first step, I express fixed effects $\{\delta_{jt}\}_{j,t}$ as a function of parameter vector θ_2. Under the assumption that ε_{ijt} in (3.1) follows the type I extreme value distribution, I calculate the predicted market share s_{jt} of car j in year t as follows:

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

where $D_i = (y_i, h_i')'$ and $v_i = (v_{i\alpha}, v_{i\rho})'$ and $F(\cdot)$ and $G(\cdot)$ are cumulative distributions of D_i and v_i, respectively. I compute the multiple integrals in the market share s_{jt} by simulation.[15] Using the predicted market share s_{jt} and observed market share S_{jt}, I define a contraction mapping $T(\delta)$ as proposed by Berry (1994) and BLP (1995):

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

I find that the predicted market share s_{jt} matches the observed market share S_{jt} at a fixed point of the mapping $T(\delta)$. Given the parameter θ_2, I solve for the 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 obtain the fixed point for $T(\delta)$ as the convergent point when iterating the calculation until $\|\delta_{jt}^{h+1} - \delta_{jt}^{h}\|_\infty < \epsilon^{tol}$ is satisfied and back out the fixed point $\delta_{jt} = s_{jt}^{-1}(S_{jt}, \theta_2)$.[16] The crucial point here is that all the fixed effects $\{\delta_{jt}\}_{j,t}$ are expressed in the function of parameter θ_2. This implies that the number of parameters to be estimated by nonlinear search in MLE decreases dramatically.

As the second step, I estimate θ_1 using the fixed point δ_{jt} obtained in the previous step. Recall that δ_{jt} in (4.1) can be written as

$$\delta_{jt} = -\alpha_0 r_{jt} + w_{jt}'\psi + \xi_{jt}. \tag{4.2}$$

Since assuming that rental price r_{jt} correlates with unobservable attribute ξ_{jt}, I estimate parameters α_0 and ψ by the generalized method of moments (GMM). For the GMM estimation, I prepare a $L \times 1$ vector z_{jt} as an instrument for r_{jt} that satisfies moment conditions $E[z_{jt}\xi_{jt}] = 0$. Given parameter θ_2, the GMM estimates $\hat{\theta}_1$ are defined as

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

[15] I generate R times random numbers from demographic and stochastic variable distributions and denote them as v_{iD}^r and v_i^r $(r = 1, \ldots, R)$. In this study, I construct the distribution $F(\cdot)$ using the CSLC data. With these random draws, I approximate market share s_{jt} as follows:

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

[16] I set the tolerance criterion ϵ^{tol} at 10^{-12}.

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 and a consistent estimate of $E[\xi_{jt}^2 z_{jt} z_{jt}']^{-1}$. In estimation, I implement the two-step GMM by setting $W = (Z'Z)^{-1}$ in the first-stage estimation.

Finally, for the estimation of θ_2, I define a likelihood function based on individual car choice and mileage choice. When household i purchases car j in year t, let $\tilde{M}_{ijt}$ denote the observed annual mileage and η_{ijt} be the error between the log of observed mileage $\tilde{M}_{ijt}$ and the log of mileage predicted by the model M_{ijt},[17]

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

Moreover, assuming that η_{ijt} follows a normal distribution with mean zero and variance σ_η^2, it follows that the conditional density of observing $\tilde{M}_{ijt}$ takes the form

$$\ell\left(\tilde{M}_{ijt} \middle| i \text{ chooses } j \text{ at } t,\ X_{ijt}\right) = \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left\{-\frac{1}{2}\left(\frac{\log \tilde{M}_{ijt} - \log M_{ijt}}{\sigma_\eta}\right)^2\right\},$$

where $X_{ijt} = (x_{jt}', p_{jt}^M, w_{jt}', D_i', v_i')'$. In the expression, $\log(M_{ijt})$ is the log of the driving demand obtained in (3.4). Denoting $\tilde{\theta}_2 = (\theta_2, \sigma_\eta)$, I define the likelihood function for each household $L_{ijt}(\tilde{\theta}_2)$ as[18]

$$L_{ijt}(\tilde{\theta}_2) = \int \left[\frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left\{-\frac{1}{2}\left(\frac{\log \tilde{M}_{ijt} - \log M_{ijt}}{\sigma_\eta}\right)^2\right\} \cdot \frac{\exp(V_{ijt})}{\sum_{k=0}^{J_t} \exp(V_{ikt})}\right] dG(v_i).$$

In the integral of this function, the first term of the multiplication expresses the density of mileage conditional on purchasing car j, and the second term expresses the choice probability of the car. Therefore, this likelihood function forms the joint probability of car choice and use, allowing for joint estimation of parameters in the two demand equations. I approximate 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 written as

$$\sum_{t=1}^{T} \sum_{i=1}^{N_t} \sum_{j=1}^{J_t} d_{ijt} \cdot \log \check{L}_{ijt}(\tilde{\theta}_2),$$

[17] Following Bento et al. (2009) and D'Haultfœuille et al. (2014), I assume that error η_{ijt} is independent of the car choice decision of households. Under this assumption, although I construct joint demand for cars and use, accounting for unobservables that enter both demands through random coefficients, the possibility of overestimating the rebound effect remains (Dubin and McFadden, 1984; Newey, 2007). However, because the model in this study allows for estimating parameters in the driving demand equation controlling for fixed effects δ_{jt}, car attributes x_{jt}, and demographics h_i, I expect that the biases of the estimates to be small compared with the results of Bento et al. (2009) and D'Haultfœuille et al. (2014).

[18] Note that the likelihood function does not include the probability of choosing the outside option because the household survey used in this study is targeted at households who purchased cars in the preceding years and does not include any information about households who have not purchased cars.

where $d_{ijt} = 1[i \text{ chooses } j \text{ at } t]$. I maximize the above objective function, with the parameters θ_1 being replaced with the estimates $\hat{\theta}_1$.[19]

In the supply model, marginal cost mc_{jt} is a parameter to be estimated. Based on the estimates of the demand parameters, I obtain the following expression for marginal costs 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

I face a price endogeneity issue in estimating the demand parameters. In the automobile market, there are many cases where vehicle models with a high market share are sold at higher prices. I can interpret this phenomenon as automobile manufacturers assigning high prices to high-quality vehicles. This fact produces the correlation between car prices and unobserved attributes such as product quality and brand image. Following BLP (1995), I then assume a possibility that rental price r_{jt} is correlated with unobserved attribute ξ_{jt}. Since I expect a positive correlation between them, the coefficient of the rental price will be overestimated in a positive direction if the endogeneity issue is ignored.

I address this endogeneity problem using an instrumental variable approach. I construct a vector of instrument variables z_{jt} that satisfies the following condition:

$$E[\xi_{jt}|z_{jt}] = 0$$

For the instruments, I consider tax-location instruments following Konishi and Zhao (2017) and Kitano (2022). The tax-location instruments are constructed based on tax reduction amounts applied under the feebate scheme, which I will explain in Appendix Section A.1. There are two advantages to using the tax reduction amounts as instruments. First, under the feebate scheme in Japan, tax reduction amounts are determined by observed vehicle attributes, such as fuel economy, weight, and engine displacement. Thus, I expect the tax reduction amounts to be uncorrelated with the unobserved attribute ξ_{jt} after controlling for the vehicle attributes in the demand estimation and to satisfy the exclusion restriction. Second, the Japanese feebate underwent several scheme changes during the study period, so the tax reduction amounts applied for each vehicle model change over time. As a consequence, the tax reduction amounts have two-dimensional variation across vehicles and over time. I construct tax-location instruments based on the tax reduction and

[19] Note that although α_i appears in the constant term of the driving demand expression defined in (3.4), it primitively captures the relationship between the quantity demanded for vehicles and the prices and thus should not be estimated from the driving demand expression but from the expression for δ_{jt} in (4.2). Therefore, I first retrieve α_0 by running the regression in (4.2) with the parameter θ_2 holding fixed and, thereafter, maximize the simulated log-likelihood function with the estimate $\hat{\alpha}_0$ being embedded in the constant term for driving demand M_{ijt}.

subsidy amounts. Specifically, I use as the instruments 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.[20] Moreover, I also use the per-kilometer operating cost p_{jt}^M and car attribute w_{jt} as instruments since they are assumed to be uncorrelated with ξ_{jt}.

Other parameters in the demand model are identified by exploiting several variations in the sample. Since parameters β, γ, and ρ are coefficients of interaction terms between car and household attributes in the indirect utility function, I expect that they are identified from the joint distribution of car ownership and household demographics. For the identification of the heterogeneity of households' preferences, I need a micro-level variation other than the car choice variation across households. Parameters in the random coefficients are thus identified from the variation in travel distances and in car choices across households. In addition, parameter λ appears in the second term of the indirect utility function and captures the degree to which factors determining driving demand affect car choice. Therefore, λ is also identified by the variations in car choice and travel distance across households. Finally, since parameter vector ψ appears only in the car choice expression, I expect ψ to be estimated from the variation in car purchase decisions across households.

On the supply side, the parameter to be estimated is the marginal cost mc_{jt}. The identification of this parameter relies on the demand parameters. In particular, the variation in car prices and market share across models and years allow me to identify the marginal cost mc_{jt}.

5 Empirical Results

In this section, I present the estimation results for the demand and supply models. Table 3 displays the results of the demand estimation. As a robustness check, Table 3 lists the results obtained by using the BLP instruments and the tax-location instruments. In the 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 GMM regression results. The estimates of the rental price coefficient α_0 obtained by both instruments are similar and statistically significant. In addition, the results indicates 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

[20] I exclude the tax reduction and subsidy amounts themselves from the instruments because of their performance in the first-stage estimation. In addition, as I explain in Section A.1, three taxes are applicable for the tax break under the feebate scheme during the study period: the acquisition tax, the tonnage tax, and the automobile tax. As Kitano (2022) notes, because the acquisition tax is an ad valorem tax, it is correlated with the unobservable ξ_{jt} and fails to satisfy the exclusion restriction. As such, I construct the tax-location instruments based on the tax reduction amounts of the tonnage tax and automobile tax, in addition to the amount of subsidy provided under the feebate policy.

Table 3: Estimation Results

		(1)		(2)	
	Coefficients	Est.	S.E.	Est.	S.E.
Panel A. Results of regression of δ_{jt} by GMM					
Rental price	α_0	11.799	0.754	11.208	0.759
Horsepower/Weight	ψ_1	31.651	5.037	30.123	5.067
Size	ψ_2	12.352	1.934	10.857	1.969
Kei-car dummy	ψ_3	36.091	3.139	34.794	3.166
AT/CVT	ψ_4	1.154	0.420	1.050	0.423
Hybrid dummy	ψ_5	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		6.960		19.590	
Hansen J statistic (d.f.)		16.389 (8)		1.707 (2)	
Panel B. Result of the DCC model by MLE					
Mean parameters:					
Rental price × income	α_1	-0.232	0.025	-0.222	0.012
Constant	λ	1.932	0.311	1.991	0.333
Horsepower/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
Standard deviation parameters:					
Rental price	σ_α	1.202	0.136	1.138	0.057
Cost of driving per kilometer	σ_ρ	0.793	0.006	0.789	0.006
Error term in the driving demand eq.	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: This table reports estimation results with 2,000 random draws. The estimations are run with the family size measured per 100 persons, the age of household head measured by age times 0.001, and the Kei-car dummy and urban dummy multiplied by 0.1. For the other variables, I follow the units listed in Table 1.

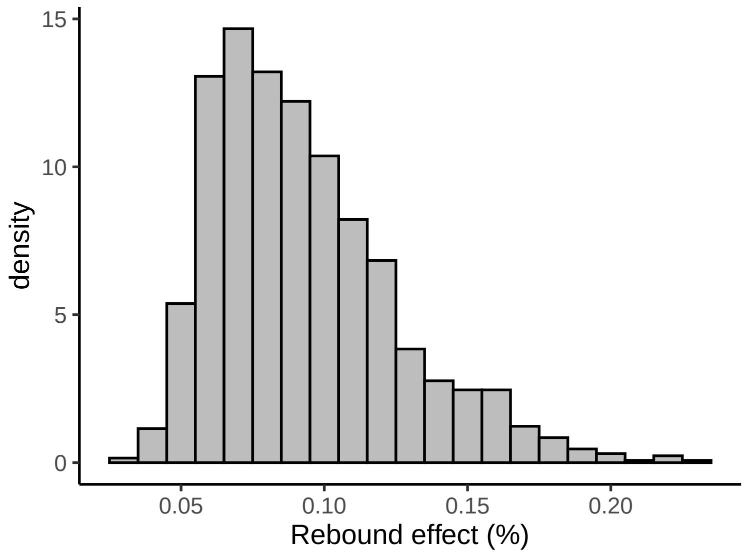

Figure 2: Heterogeneity of the Rebound Effect

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 estimate of the rebound effect is calculated based on the results in Table 3. Panel B in the table shows that both the estimates of the mean parameter ρ and variance parameter σ_ρ of the random coefficient ρ_i are statistically significant. With these estimates, I obtain the estimate of the rebound effect by calculating the elasticity of driving demand M_{ijt} with respect to the driving cost p_{jt}^M as follows:

$$\frac{\partial M_{ijt}}{\partial p_{jt}^M}\frac{p_{jt}^M}{M_{ijt}} = -\rho_i p_{jt}^M$$

Figure 2 displays the histogram of the rebound effect calculated using the estimates of model 2 in Table 3. The figure shows that the mean value of the estimated rebound effect is 0.09, meaning that a 1% decrease in the per-kilometer cost of driving will increase driving demand by 0.09%. Figure 2 also confirms that the rebound effect is unevenly distributed across households, with an interquartile rage of 0.07–0.11%. Moreover, compared with the estimate from the structural model, I find that the OLS estimate obtained in Section 2.3 is biased upward and significantly overestimates the rebound effect in absolute value. Existing studies show that estimates of the rebound effect differ substantially with the type of data set and estimation model (e.g., Graham and Glaister, 2002; Gillingham et al., 2016). However, the estimate of the rebound effect in this study falls in the range of estimates obtained in the most recent studies.[21] Indeed, my estimate, obtained by

[21] Gillingham et al. (2016) review recent empirical studies on the rebound effect and conclude that the short- and

Table 4: Elasticities, Marginal Costs, and Markups

	Mean	St. 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 shows estimates of marginal costs and markups for all firms during the sample period, 2006-2013. The markups are defined as $(p-mc)/p$. The 1st Q. and 3rd Q. in the table stand for the first and third quantiles.

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.[22]

Table 4 presents 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.[23] In addition, the estimated markups are, on average, approximately 27%. These estimates are comparable to those found in BLP (1995) and Grigolon et al. (2018) using data from the United States and European countries, respectively.

6 Counterfactual Analysis

I perform counterfactual analyses based on the estimated parameters to examine the efficiency and distributional effects of the fuel tax and the feebate policy. I also conduct a decomposition analysis of CO_2 emissions to demonstrate the contribution of the rebound effect to environmental externalities in various policy scenarios. I first describe the policy scenarios assumed in the analyses and then assess the policy impacts on various outcome variables and welfare.

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.

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

[23] For comparison, I report that the sales-weighted average of the own-rental price elasticities in 2012 is -3.55. Konishi and Zhao (2017), who use quarterly data from Japan for almost the same period as this study, report a sales-weighted average of elasticities in 2012 of -2.66. Although my estimate indicates a larger value in absolute magnitude than that of Konishi and Zhao (2017), note here that the estimate of Konishi and Zhao (2017) is not for the rental price elasticity but for the price elasticity.

Table 5: List of Counterfactual Scenarios

Scenarios	Fuel tax	Tax measures	Subsidy
[1] Baseline	0	No	No
[2] Pigouvian fuel tax	4,000	No	No
[3] Fuel tax at current tax rate in Japan	21,603	No	No
[4] Actual feebate scheme	0	tax reduction	Yes
[5] Alternative feebate: product subsidy	0	No	Yes
[6] Alternative feebate: product tax	0	tax increase	No

Note: The unit of the fuel tax is JPY per ton of CO_2. The tax measures and the subsidy indicate tax measures for automobile-related taxes and subsidy programs applied at the time of purchase, respectively.

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 and three feebate policy scenarios. Based on the estimated parameters, I simulate a baseline scenario in which neither fuel tax nor feebate policies are enforced. The remaining scenarios are generated and introduced into the baseline to assume situations in which fuel taxes at different tax rates and feebate policies 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.[24,25] 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 set at 0.76 JPY/ℓ (289 JPY/ton of CO_2) since 2016.[26] Thus, the price of gasoline p_t^{gas} that

[24] The existing tax on gasoline 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 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).

[25] The diesel is imposed a diesel handling tax of 32.1 JPY/ℓ.

[26] 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.

households face in year t is written as[27]

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

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.

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 impact 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 $p_t^{pre\text{-}tax}$.[28,29] 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).[30]

6.1.2 Feebate Schemes

In the remaining scenarios, I examine the effects of the feebate policies implemented in Japan and alternative feebate schemes.

Actual Feebate Scheme The fourth scenario assumes a situation where the feebate scheme implemented in Japan during the sample period is introduced into the baseline scenario. As described in Section 2.2, the Japanese feebate scheme is essentially a rebate program, consisting of a tax incentive measure for automobile-related taxes and a subsidy program for fuel-efficient vehicles. Here, let T_{jt} denote a vector of automobile-related taxes and $p(p_{jt}^e, T_{jt})$ denote a function of the tax-exclusive vehicle price p_{jt}^e and T_{jt} that represents the total amount of taxes paid by a new car

[27] For expositional simplicity, I omit the excise tax τ^{ex} on fuel prices in the main body of the paper. In practice, however, the excise tax τ^{ex} is imposed on gasoline and diesel prices, and thus 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

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

where $\tau^{petroleum}$ represents the petroleum and coal tax of 2.04 JPY/ℓ and τ^{diesel} represents the diesel handling tax rate of 32.1 JPY/ℓ. I use these formulas in the analysis below.

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

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

[30] For diesel, I set different tax rates from gasoline and add to the pre-tax price of diesel the tax rate of 34.9 JPY/ℓ, which is the sum of the pre-existing fuel tax rate and the additional carbon tax rate.

purchaser at the time of purchase. See Appendix A.1.1 for details on the automobile-related taxes during the sample period in Japan. With the function, the tax-inclusive vehicle price p_{jt} under the feebate scheme is written as

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

where tr_{jt} denotes a vector of tax reduction rates and ES_{jt} is the amount of subsidy for fuel-efficient cars. The tax reduction rates and the subsidy amount are determined according to fuel economy standards. See Appendix A.1 for details.

Alternative Feebate Schemes I consider alternative feebate schemes in the fifth and sixth scenarios. Specifically, I design a product subsidy and a product tax, such that each of them determines the subsidy amounts and the tax burden based solely on the vehicle's CO_2 emissions per kilometer. Under the product subsidy and product tax schemes, the tax-inclusive prices p_{jt} are determined as follows:

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

and

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

In the expressions, τ^E represents the subsidy/tax rates in each scenario, and e_{jt} denotes CO_2 emissions per kilometer (kg-CO_2/km) from driving car j in year t.[31] For comparison with the policy effects of the actual feebate scheme and the fuel tax, I set each τ^E such that the product subsidy and the product tax achieve the same environmental externalities as those caused by the actual feebate and the current fuel tax, respectively.

6.2 Measure of 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).[32] See Appendix A.3 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 consumer surplus due to a policy change is calculated as follows:

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

[31] Per-kilometer CO_2 emissions e_{jt} 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).

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

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:

$$PS = \sum_{f \in \mathcal{F}} \sum_{j \in \mathcal{J}_{ft}} \left(p_{jt}^e - \widehat{mc}_{jt}\right) N_t s_{jt}(r_t),$$

$$TR = \int\int \sum_{f \in \mathcal{F}} \sum_{j \in \mathcal{J}_{ft}} \left(p\left(p_{jt}^e, dr_{jt} \cdot T_{jt}\right) - ES_{jt} + T_{ijt}^{fuel}\right) N_t s_{ijt}(r_t)\, dF(D_i)\, dG(v_i),$$

$$EXT = \text{SCC} \times \int\int \sum_{f \in \mathcal{F}} \sum_{j \in \mathcal{J}_{ft}} e_{jt} M_{ijt} N_t s_{ijt}(r_t)\, dF(D_i)\, dG(v_i),$$

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.[33] 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 feebate policies. Consequently, I define the sum of the above as the total surplus (TS).

6.3 Simulation Results

6.3.1 Policy Impacts on Outcome Variables

I first examine the impacts of the policy changes on the outcome variables. Table 6 reports the mean values of the outcome variables obtained under each policy scenario using the sample for 2012. The table confirms that fuel taxes are less likely to affect the equilibrium prices of automobiles, which is consistent with the results of Grigolon et al. (2018) and Tan et al. (2019). While the fuel tax at current tax rate moderates total VKT by 22% relative to the baseline scenario, it results in an additional reduction of fuel usage because it improves 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 actual feebate scheme has significant impacts on the outcomes. As expected, the actual feebate scheme boosts the sales of automobiles, particularly the sales of fuel-efficient vehicles, raising the equilibrium tax-exclusive prices relative to the baseline scenario. I find that the feebate increases sales volume by 27% on average and improves the sales-weighted average of fuel economy in 2012 by 3.6% relative to the baseline scenario. Moreover, the feebate also drives up fuel usage. I investigate the channels through which the feebate augments fuel usage by decomposition analysis in Section 6.4.

Table 6 also presents the impacts of the alternative feebate schemes on outcomes. I perform a grid search to obtain the rate of subsidy/tax τ^E for each alternative scheme.[34] Table 6 shows that the product subsidy achieves the same fuel usage as the actual feebate without entailing a reduction

[33] 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).

[34] For the product subsidy, τ^E works out to 15,311 JPY per kg-CO_2 per kilometer such that the product subsidy achieves the same externality as the actual feebate, and for the product tax, 1.21 million JPY per kg-CO_2 per kilometer

Table 6: Impacts of Policies on Various Outcomes in 2012

Scenarios	Tax-exclusive price p^e_{jt} (million JPY)	Tax-inclusive price p_{jt} (million JPY)	Sales	VKT (10,000km)	Fuel usage (kℓ)
[1] Baseline	2.378	2.672	23,483	13,664	7,571
[2] Pigouvian fuel tax	2.378	2.672	22,892	13,034	7,179
[3] Current fuel tax in Japan	2.378	2.672	20,465	10,651	5,728
[4] Actual feebate scheme	2.382	2.594	29,930	17,365	9,285
[5] Product subsidy	2.376	2.669	30,542	17,424	9,285
[6] Product tax	2.385	2.679	17,920	10,574	5,728

Note: This table reports the mean values for each outcome variable.

in sales volumes. On the other hand, the product tax considerably decreases sales volumes relative to the fuel tax. This is because the product tax must ensure the same fuel usage as the fuel tax by reducing the sales volumes to control total driving demand, while the fuel tax can achieve the same objective by directly suppressing driving demand.

Apart from the policy scenarios assumed in the simulation, how will a future carbon tax increase in Japan affect outcomes? Figure 3 displays the changes in several outcome variables when different carbon tax rates τ^{carbon} of 289, 1000, 3000, 5000, and 10,000 JPY/ton of CO_2 are introduced into the pre-existing fuel tax τ^{gas}. Regarding the graph for CO_2 emissions in the bottom-right figure, I find that the total CO_2 emissions amount to approximately 2.20 million tons of CO_2 when the additional carbon tax is zero.[35] When the carbon tax of 10,000 JPY/ton of CO_2 (26.2 JPY/ℓ) is added, the CO_2 emissions decline by 10.3%, meaning that a 1% increase in the additional carbon tax leads to a 0.22% reduction in CO_2 emissions in Japan. Similarly, I find that the elasticities of the equilibrium price, demand, and fuel economy with respect to the carbon tax are 0.0002%, −0.12%, and 0.01%, respectively.

6.3.2 Welfare Effects

In this section, I examine the welfare effects of the policies. Table 7 shows the results using the sample for 2012. The first row in this table reports the welfare in the baseline scenario, while the

such that the product tax achieves the same externality as the current fuel tax rate. Under these subsidy/tax rates, the product subsidy scheme provides new car purchasers with subsidies of 45,505–233,459 JPY with an average of 107,489 JPY, and the product tax scheme imposes tax burdens of 79,044–405,532 JPY with an average of 190,632 JPY.

[35] This situation corresponds to that where the fuel tax rate equates to the pre-existing fuel tax rate of 55.84 JPY/ℓ.

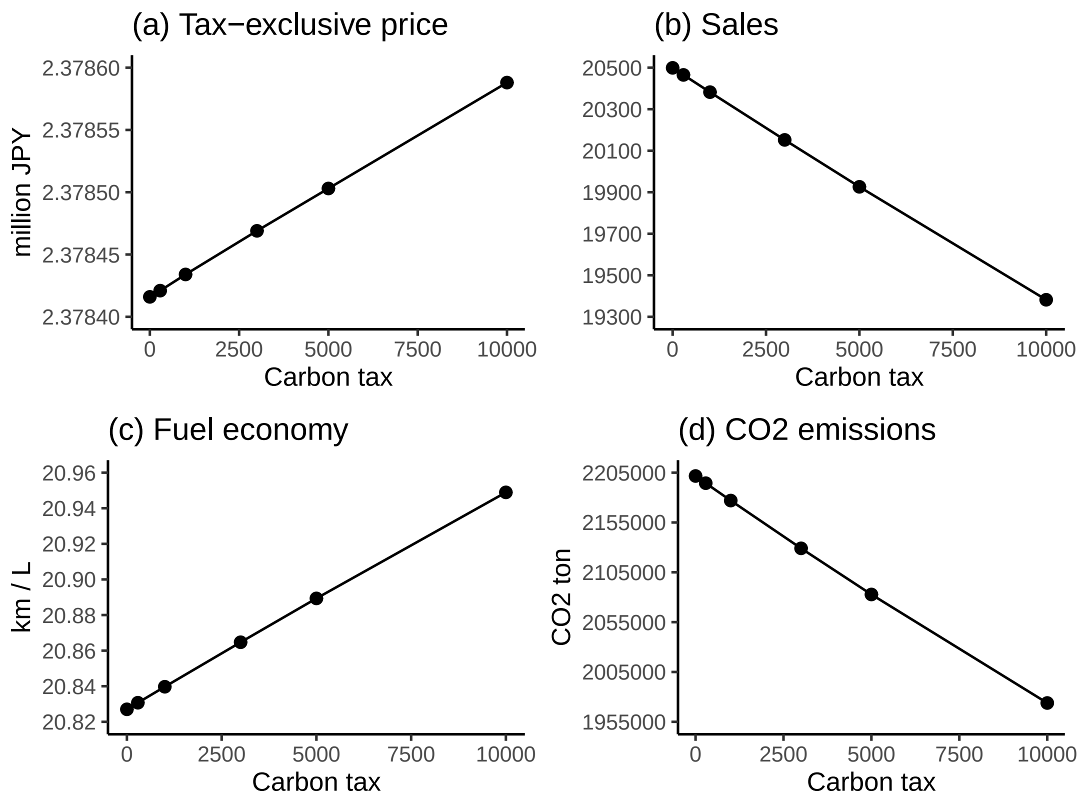

Figure 3: Effects of Additional Carbon Taxes

Note: The graphs show the changes in the sales-weighted average of tax-exclusive vehicle prices, sales, the sales-weighted average of fuel economy, and the total CO_2 emissions from driving cars purchased in 2012 when carbon taxes of 289, 1000, 3000, 5000, and 10,000 JPY/ton of CO_2 are added to the pre-existing fuel tax.

remaining rows compare the welfare in each scenario with that obtained in the baseline. Table 7 confirms that the fuel taxes reduce environmental externalities with low burdens on consumers and producers. In fact, the fuel tax with the current tax rate reduces the externality by 24% compared to the baseline scenario while it increases the total revenues, or the tax burden, by approximately 5%, suggesting that the fuel tax effectively reduces the environmental externality.

Moreover, Table 7 shows that the total surplus declines with the fuel tax rate. The explanation for the decline in total surplus due to the Pigouvian fuel tax requires me to separately consider the changes in welfare in the automobile and fuel markets. As indicated in Table 7, the decrease in total surplus due to the fuel tax comes primarily from the decrease in producer surplus. Furthermore, I find that the decrease in the consumer surplus comes primarily from that arising in the fuel market targeted by households' continuous choices, and the remaining decrease in consumer surplus arising in the automobile market targeted by households' discrete choices is relatively small.[36] This finding

[36] This is due to the following reason. Table 7 confirms that fuel tax revenue almost equates to the environmental

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

Scenarios	CS	PS	TR: Automobile-related taxes	TR: Fuel tax	TR: Feebate	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 feebate scheme	+134	+552	+79	±0	-172	+2.6	+591
[5] Product subsidy	+145	+492	+66	±0	-165	+2.6	+535
[6] Product tax	-116	-419	-66	±0	+97	-2.8	-501

Note: The first row lists the welfares obtained 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 the automobile-related taxes and the feebate schemes 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.

implies that the welfare loss borne by producers under the fuel tax scenario is the main driver of the decrease in total surplus, and even the Pigouvian tax on fuel does not necessarily improve the overall economic welfare in the two markets.

In contrast to the fuel taxes, the actual feebate augments the environmental externalities, while it raises the total surplus by 591 billion JPY in 2012 relative to the baseline scenario. Table 7 confirms that a significant majority of this welfare gain comes through increases in consumer surplus 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 feebate plays a role in mitigating the market distortions (Buchanan, 1969; Fowlie et al., 2016).

Here, as shown below, the validity of the predicted result is ensured for the actual feebate scheme. Table 7 reports that the annualized feebate expenditures applied to the rental prices paid by car owners in 2012 equal 172 billion JPY, implying that an estimate of the feebate expenditures in 2012 amounts to about 630 billion JPY in total. The actual expenditure for the subsidy program alone, which is a program of the feebate schemes, was 274.7 billion JPY in 2012. Therefore, when the expenditure for the subsidy program is added to the budget for the tax incentives, which is

externality from driving, offsetting this negative externality in the fuel market. In addition, the fuel tax revenue and the decrease in consumer surplus in the fuel market should be of roughly the same magnitude because the estimated rebound effect implies that driving demand is inelastic to the cost of driving per kilometer. Therefore, I find that the remaining decrease in consumer surplus occurs in the automobile market, which accounts for a small portion of the total decrease in consumer surplus.

another program composing the feebate scheme, I find that the sum of these expenditures is close to the estimated expenditure above.[37]

Table 7 also reveals the welfare effects of alternative feebate schemes. Table 7 demonstrates that the externality-equivalent product subsidy is less costly and yields a slightly higher consumer surplus than the actual feebate scheme. The fact that the product subsidy determines the amount of the subsidy depending solely on the CO_2 emissions per kilometer helps the product subsidy to improve the sales-weighted fuel economy relatively easily and achieve the same externality as the actual feebate, with less expenditures for implementation.[38]

On the other hand, compared with the externality-equivalent product tax, I find that the fuel tax at the current tax rate achieves a higher total surplus. In particular, the product tax substantially reduces the consumer surplus and the producer surplus relative to the fuel tax, which is consistent with the result presented in Table 6. Moreover, I find that the fuel tax requires fewer resources than the externality-equivalent product tax. Table 7 reveals that the product tax is approximately 1.7 times more costly than the fuel tax in reducing environmental externalities by the same amount. The results suggest that the fuel tax is more cost-effective than the product tax.

6.3.3 Distributional Impacts

In this section, I analyze the distributional impacts of policies. In particular, I investigate how the distributional impacts differ between a fuel tax and a feebate policy and between feebate scheme designs. Through the analyses, I present arguments on the regressivity of the fuel tax and the feebate policy.

Figure 4 displays the rates of change of several variables by income quintile when policies are introduced into the baseline scenario. The figures on the top show that the distributional impacts differ considerably between the fuel tax and the externality-equivalent product tax. The fuel tax with the Japanese current tax rate decreases sales volume and suppresses distance traveled evenly in all income groups, while its impact on the average fuel economy of purchased vehicles differs by income quintile. Figure 4 suggests that the fuel tax induces high-income households to improve their fuel economy, indicating that high-income households that drive long distances particularly react to the introduction of the fuel tax by purchasing fuel-efficient vehicles to save on driving costs. However, since low-income households already tended to purchase fuel-efficient vehicles before the introduction of the fuel tax, the improvement in average fuel economy in the low-income groups is relatively small. In contrast, the externality-equivalent product tax substantially decreases sales,

[37] Note that since the subsidy program in the second period was completed by September 2012 because of budget constraints and this study using yearly data does not control for monthly regulatory effects, my estimate of the resources used for the feebate is likely to overestimate the actual value.

[38] The product subsidy decreases the producer surplus and the tax revenue from the automobile-related taxes relative to the actual feebate scheme because the product subsidy decreases the sales of fuel-inefficient vehicles with relatively large sizes compared with the actual feebate scheme.

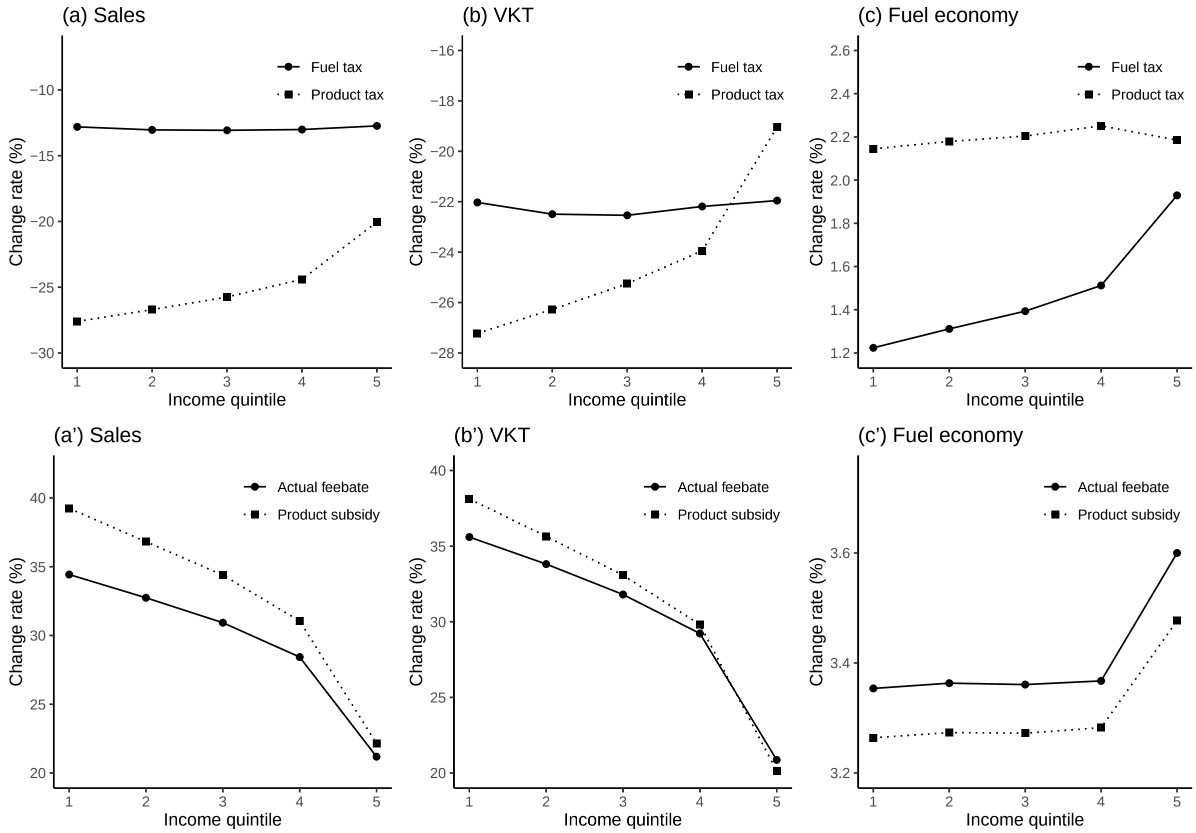

Figure 4: Policy Impacts on Various Outcomes by Income Quintile

Note: The graphs display the policy impacts on the sales, 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 product tax on the top and those of the actual feebate and the externality-equivalent product 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.

particularly in the low-income class, and in turn reduces the distance traveled in that income group.

The figures on the bottom show approximately the same trends of the change in variables across the actual feebate and the externality-equivalent product subsidy; however, the amount of change differs. In particular, it is remarkable that while both policies increase the sales in any income class, the product subsidy significantly drives up sales in the low-income classes relative to the actual feebate. This is because the product subsidy is designed to provide fuel-efficient vehicles such as Kei-cars that households in the low-income class tend to purchase with substantial subsidies.

Table 8 reports that 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 and the product tax. The change in consumer surplus as a percentage of CO_2 reduction can be interpreted as a shadow cost of a policy. Table 8 shows that each of the policies burdens households in the lowest-income group with a shadow cost of approximately 97,000 JPY and 170,000 JPY to reduce a ton of CO_2

Table 8: Shadow Costs of Policy Implementation

	Fuel tax		Externality-equivalent product tax	
Income quintile	$\lvert\Delta$CS$\rvert$/CO_2 ton (JPY)	$\lvert\Delta$CS$\rvert$/income	$\lvert\Delta$CS$\rvert$/CO_2 ton (JPY)	$\lvert\Delta$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 and the product tax in 2012 by income quintile. The fuel tax rate is set at the current tax rate of 21,603 JPY/ton of CO_2. $\lvert\Delta$CS$\rvert$ represents the absolute value of the change in consumer surplus from the no-policy baseline.

on average for the fuel tax and the product tax, respectively. Here, the shadow cost of the fuel tax indicates a larger value than the fuel tax rate of 21,603 JPY/ton of CO_2. This can be attributed to the fact that the fuel tax causes households not only to control their driving demand but also to forgo the purchase of a car to reduce a ton of CO_2. In addition, the result suggests that in terms of the shadow costs, the fuel tax is 1.7 times less costly than the product tax in all income classes.

Furthermore, Table 8 shows that the shadow costs of the two policies fall with the income level. I find that because low-income households already own fuel-efficient vehicles and drive shorter distances before the imposition of taxes, the additional costs for CO_2 abatement are high for low-income households. In contrast, high-income households have greater potential to abate a ton of CO_2 than low-income households, and thus the shadow costs are relatively low for high-income households.

Table 8 also shows that the changes in consumer surplus as a percentage of income are larger for the lower-income classes under each of the two policies. Specifically, I find that both the fuel tax and the product tax are regressive until the fourth quintile and become progressive in the highest income group. Comparing the regressivities between the two policies, although the difference is quite small, the product tax is slightly more regressive than the fuel tax (see also Figure A.1 in the Appendix).

6.4 Decomposition of CO_2 Emissions

I conduct a decomposition analysis to identify the sources of environmental externalities arising under each policy scenario. Through the decomposition analysis of CO_2 emissions, 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 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 $CO_{2,t}(d)$ 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

$$\Delta_t = CO_{2,t}(1) - CO_{2,t}(0),$$

where

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

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 impacts 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.[39]

I decompose the change in CO_2 emissions Δ_t into the following four components:[40]

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

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

where

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

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

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

[40] The transformation for the CO_2 decomposition used in this study is slightly different from that proposed by D'Haultfœuille et al. (2014). In the decomposition of D'Haultfœuille et al. (2014), the composition effect and the rebound effect contain a part of the fleet size effect because the difference between market shares before and after policy introduction, $s_{ijt}(1) - s_{ijt}(0)$, that appears in their transformation includes not only the relative changes in market shares within the inside options $s_{ijt}^{inside}(1) - s_{ijt}^{inside}(0)$ but also the change in the aggregate market share $\sum_{j=1}^{J_t} (s_{ijt}(1) - s_{ijt}(0))$. As shown below, I modify their transformation to separate these effects.

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 composition effect, which captures an expected decrease in CO_2 emissions caused by the change in the sales mix when one assumes that driving distance remains unchanged following policy introduction. If the elasticity of driving distance with respect to a policy change is assumed to be zero, CO_2 emissions should decrease in response to the introduction of the fuel tax or the feebate; they are expected to encourage households to buy fuel-efficient cars. As such, the composition effect will be negative when the expected policy effect is sufficiently large.

In practice, however, the driving distance will change with policy status. There are two channels through which a policy change affects driving distance. The first channel is when a household changes its car choice depending on policy status d. The effect through the first channel refers to the rebound effect. In the above expression, the rebound effect captures a correlation between the deviation of $M_{ijt}(1)$ from the mean value and the change in market share within the inside options Δs_{ijt}^{inside}. The second channel arises when a household purchases the same car in either policy status $d = 0, 1$. The effect through the second channel, which I call the fuel cost effect, is the direct effect of the change in the fuel cost on driving distance. Since the feebate does not directly change the fuel cost when a household purchases the same car in either policy status, the fuel cost effect comes to zero. On the other hand, a fuel tax directly affects driving demand. This direct effect of the fuel tax is captured by the fuel cost effect. 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.[41] The table reports changes in CO_2 emissions from the no-policy baseline scenario and the contribution ratios of the four effects. As expected, the composition effect contributes to reductions in the CO_2 emissions in the actual feebate policy and fuel tax scenarios since each policy introduction changes the fleet composition and shifts sales toward fuel-efficient cars. Moreover, in both the policy scenarios, the reductions in CO_2 emissions from the composition effect are partially offset by the increases in the CO_2 emissions resulting from the rebound effect. In particular, the actual feebate scheme results in a larger rebound effect than in the fuel tax scenario. The rebound effect induced by the feebate contributes to the increase in the CO_2 emissions and cancels out approximately 7% of the decrease in emissions

[41] One point should be noted when interpreting the results in Table 9. The analysis here focuses only on the policy impacts on new vehicles purchased in the corresponding year. I expect the estimates of the fuel cost effect and the fleet size effect to change when considering the impacts on vehicles already owned by households who choose the outside option in a given year. Because the fuel tax impacts not only the mileage of vehicles purchased in the year but also the mileage of vehicles already owned, the fuel cost effect becomes larger than that reported in Table 9. Additionally, the magnitude of the fleet size effect decreases because policies are expected to reduce CO_2 emissions from old fuel-inefficient vehicles by replacing them with new fuel-efficient vehicles. For these reasons, I here focus only on the estimates of the composition effect and the rebound effect.

Table 9: CO_2 Decomposition

	Fuel tax		Actual feebate	
	Δ_t	%	Δ_t	%
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 and the contribution rate (%) of the four effects calculated using the 2012 sample. The unit of Δ_t is 1,000 tons of CO_2. 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.

resulting from the composition effect.

In contrast, the fuel tax succeeds in controlling the rebound effect. Table 9 confirms that the increase in CO_2 emissions due to the rebound effect is offset by the decrease in emissions due to the fuel cost effect. Finally, Table 9 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 welfare effects of the fuel tax and feebate policies in the Japanese new car market. To answer the empirical questions posed in the introduction, I evaluate the performance of feebate policy as a green economic stimulus program and the regressivity of the two policies, with emphasis on efficiency and distributional equity. I employ a model with two decisions—on car ownership and utilization—on the demand side and identify model parameters by using both micro-level data from a household survey and macro-level aggregate data. Hence, with respect to methodology, this study is in line with a strand of the micro BLP literature, such as Petrin (2002), Berry et al. (2004), and Goolsbee and Petrin (2004), in which a method is developed that allows for more robust identification of parameters by adding moment conditions formed by micro-level data to those established using aggregate data.

The results obtained in my study have the following two implications. The first implication highlights the importance of accounting for the rebound effect in evaluating energy efficiency programs. Prior studies that analyzed the extent to which programs, such as an appliance replacement program, 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; Fowlie et al., 2018; and Levinson, 2016). In this paper, 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 feebate policy in the automobile market. Through a decomposition analysis, I find that the rebound effect induced by the feebate cancels out approximately 7% of the reduction in CO_2 emissions that would originally have been attained by the fuel economy improvement. Overall, counterfactual analyses show that the Japanese feebate policy stimulates demand but augments environmental externalities. These results suggest that the feebate policy alone fails to simultaneously achieve both economic and environmental goals.

The second implication relates to the efficiency and equity of a fuel tax and a product tax. The counterfactual analysis reveals that the fuel tax at the current tax rate in Japan is 1.7 times less costly than the externality-equivalent product tax and that there is no difference in terms of regressivity between the two policies. Currently, in Japan, there is discussion of simplifying the automobile-related taxes that determine the tax amounts according to a vehicle's weight and displacement. The results in my study suggest that social welfare could be increased without relatively increasing the tax burden on low-income households by substituting the existing product taxes, such as the tonnage tax and the automobile tax, for a revenue-neutral carbon tax.

I acknowledge some limitations to this study. First, I do not consider misperception of fuel costs by households in facing the vehicle choice. For example, Grigolon et al. (2018) assume the situation in which households, at the time of purchase, undervalue the future fuel cost savings obtained by purchasing fuel-efficient cars and evaluate the welfare effects of a fuel tax and a product tax, with the belief error being included. Although Grigolon et al. (2018) and other papers studying this issue show that there is little such undervaluation by households, if it is substantial, my study may underestimate the social welfare of the feebate policy. Second, I use static models on the demand and supply sides and particularly in the supply model, treat only prices as a variable that firms can manipulate endogenously. As such, the estimation results should be interpreted as short-term policy impacts. Designing a model to account for the dynamic responses of households and firms is required to analyze the long-term effects of the fuel tax and feebate. Finally, I need to undertake a more careful analysis of optimal policy for the automobile market and the fuel market targeted by the DCC model. A discussion of the optimal policy for the two markets is expected to become more complicated when the introduction of a policy designed to eliminate distortions in a market in turn produces distortions in the other market. I would like to make these points the subject of future work.

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A Appendix

A.1 Institutional Background of the Japanese Feebate Policy

A.1.1 Automobile-Related Taxes

In this section, I outline automobile-related taxes relating to the feebate schemes. 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.[42] 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 by the function p as follows:

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

where τ^{ex} represents the excise tax rate of 5%. The amount of the acquisition tax $T^{acquisition}_{jt}$ is proportional to the acquisition price of the purchased car.[43] 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.[44] 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).[45] The amount of the automobile tax is shown in Table A.1.

A.1.2 Feebate Scheme

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

[42] 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.

[43] In practice, the acquisition price is approximately 90% of the tax-exclusive price p^e_{jt}.

[44] The acquisition tax is not imposed when the acquisition price of a vehicle is less than 500,000 JPY.

[45] 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).

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. See Table A.3 for the target values of the fuel economy standards.[46] 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%. In 2009, the system of the tax incentive measures were changed and substantially expanded as one of the Green New Deal programs.[47] 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):

$$\begin{aligned} &\min_{p_{jt}^M, p_t^X} \quad \alpha_i \left(\frac{y_i - r_{jt}}{p_t^X} \right) + \lambda \exp \left(x_{jt}'\beta + h_i'\gamma - \rho_i \frac{p_{jt}^M}{p_t^X} \right) + w_{jt}'\psi + \xi_{jt} + \varepsilon_{ijt} \\ &\text{subject to} \quad p_{jt}^M M_{ijt} + p_t^X X_{it} = y_i - r_{jt} \end{aligned}$$

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

[46] 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. Each of the target values is used during the sample period. In particular, the 2010 target values are used in the first term and the 2015 target values in the second term to select vehicles for tax reduction.

[47] 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

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. In the requirements shown in the table, 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 (JAMA, 2006). The monetary amounts are what is deductible from the purchase price, and figures in percentage terms represent the reduction rates for each automobile-related tax. 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		

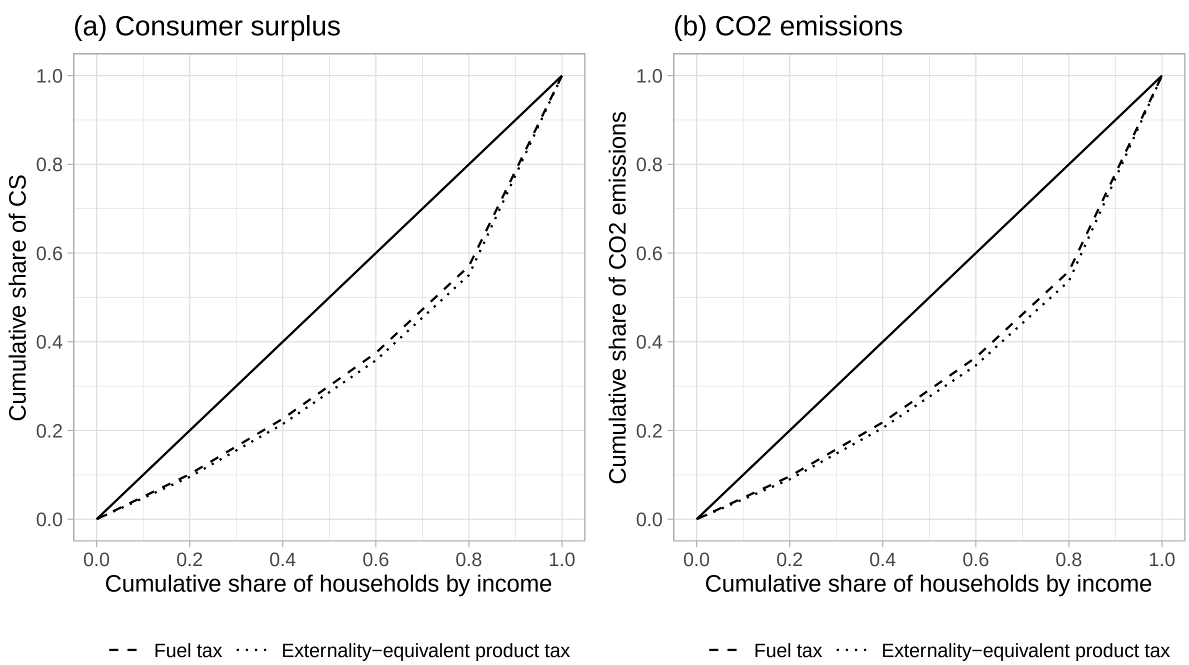

Figure A.1: Regressivity of the Fuel tax and Product Tax

Note: The figures show the Lorenz curves obtained under the scenarios for the fuel tax at the current tax rate in Japan and the externality-equivalent product tax, along with the 45-degree line. The left and right figures take the cumulative shares of consumer surplus and CO_2 emissions as the vertical axises, respectively. The 45-degree line indicates the situation in which households in each income class incur the tax burden or emit CO_2 evenly.