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Rebound Effect of Passenger Vehicles : A Case of Japanese Household

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Abstract

Promoting an energy-saving policy is one of the many ongoing strategies being implemented in Japan to combat the climate change problem. However, the anticipated energy savings from this energy-efficiency improvement program may be partially negated by an unexpected “rebound effect.” This paper estimates the rebound effect of passenger vehicles in Japan using micro data. In our sample, the rebound effect of passenger vehicles was estimated to be approximately 22%. We separate the sample into two groups: (i) the high environmental awareness group and (ii) the low environmental awareness group based on the vehicle type and whether the vehicle is targeted by the Vehicle Green Tax Plan. The rebound effect for the latter was estimated to be about 41%. On the other hand, the estimated rebound effect for the former group was statistically insignificant. Thus we conclude that to promote energy-efficiency improvement policies, the Japanese government should consider the rebound effect, and further, raising the level of environmental awareness can decrease the rebound effect.

Keywords : rebound effect, fuel efficiency, environmental awareness, passenger vehicle and Vehicle Green Tax Plan

1 Introduction

The Kyoto Protocol came into effect on February 16, 2005, and as of January 2006, it had 158 signatory countries. These countries have begun developing strategies to reduce energy use and green house gas emissions. Japan has also ratified the Kyoto Protocol and has carried out some related projects.¹⁾ Amongst these, the promotion of energy-efficiency improvement programs is one of the most important. Energy-efficiency improvement policies were introduced after the oil shocks of the 1970s. Moreover, since climate change started becoming the core issue in the 1990s, the Japanese government has further strengthened these policies. Many researchers have suggested that improving energy efficiency can lead to reduced energy usage. However, they have only estimated technical savings and disregarded actual consumer behavior. In other words, energy savings have been overestimated by ignoring market response to efficiency improvement measures : the so called rebound effect (Khazzoom, 1980).

The rebound effect is of particular concern in Japan because despite the heavy energy demands from the energy-intensive industries, transport, and household sectors, Japanese self-sufficiency rate in energy products is low at approximately 20% (including nuclear energy). To meet this demand, Japan recourses to importing a considerable amount of energy. Hence, to evaluate the effectiveness of Japanese energy-efficiency improvement policies and to assess the actual energy savings accumulated through them, it is necessary to estimate the rebound effect.

This paper focuses on the fuel consumption of passenger vehicles because as discussed in the next section, recently the government of Japan has placed special emphasis on reducing fuel consumption of passenger vehicles by implementing

1) These projects include voluntary emission trading, law for the rationalization of energy use, and development of new energy resources, among others.

efficiency improvement policies. This paper estimates the rebound effect of passenger vehicles using micro data. Furthermore, we also note the manner in which environmental awareness influences rebound effect.

2 Overview : Environmental policies for passenger vehicle in Japan

In accordance with the “Kyoto Protocol Target Achievement Plan” which was decided in 2005,²⁾ Japan has managed to ensure that greenhouse gas emissions from the industrial sector and public transportation sector (that recently accounted for 40% and 10% of Japan’s total greenhouse gas emissions, respectively) have remained unchanged in recent years. On the other hand, gas emissions from the civilian (households and operations) sector and the private transportation sector (that recently accounted for 30% and 10% of Japan’s total greenhouse gas emissions) have risen substantially. We observe that the share of the industrial sector and the goods and public transportation sector has decreased since the oil shocks, whereas that of the civilian and private transportation sector has increased continuously. Consequently, in recent years, the focus of the government’s emission reduction policy has been shifting from the former two sectors to the latter two sectors. In particular, the private transportation sector witnessed the introduction and rapid promotion of a stronger policy on energy-conservation. For example, following an amendment to the “Energy Saving Law” in 1998, all passenger vehicles sold in Japan from 1998 onwards are obligated to have consistently improved mileages, so as to achieve the mandatory target of 22.8% increase in gasoline mileage, vis-à-vis that of 1995, by 2010.³⁾ With this amendment, the development and distribution of energy saving vehicles, such as fuel-efficient vehicles, hybrid vehicles, natural gas

2) According to the Plan, the government of Japan is committed to combating climate change and seeks to reduce its greenhouse gas emissions by 6% below in 1990 emissions level, in accordance with the Kyoto Protocol.

vehicles, etc., have progressed beyond expectations. According to the reports of the Ministry of Land, Infrastructure and Transport, the fuel efficiency of an average passenger vehicle improved from 12.30km/l in 1995 to 15.10km/l in 2005. This implies that the passenger vehicle sector has achieved its target well before time. Meanwhile, for new-vehicle owners, the Japanese government introduced the "Vehicle Green Tax Plan" in 2001. Under this plan, purchasers of low-emission and fuel-efficient vehicles, which meet a certain criterion, receive preferential treatment in terms of reductions in motor vehicle tax and automobile acquisition tax. This plan boosted the sales of low-emission and fuel-efficient vehicles.^{4),5)} However, despite these efforts, the reduction in total gas emissions has not met the expectations of the Japanese government.

It is noteworthy, however, that the abovementioned environmental strategies definitely had an impact on gasoline consumption. According to an Energy Conservation Center, Japan (ECCJ) report, gasoline consumption per vehicle was 1,045 l in 1990, 1,101 l in 1997, and 1,102 l in 2001. This shows that rate of increase in gasoline consumption has in fact reduced after the amendment. However, this decline in the rate of increase in gasoline consumption may be partially negated by an increase in the distance traveled. This report also illustrates a substantial rise in the run per vehicle with 9,920km in 1990, 9,470km in 1997,

3) Moreover, the government made more rigorous mandatory target which is called "JC08" in 2007. Under "JC08", passenger vehicles have to achieve 23.5% increase in gasoline mileage, vis-à-vis that of 2004, by 2015.

4) According to the report of the Ministry of Land, Infrastructure and Transport, two thirds of new car registrations in 2002 were low-emission and fuel-efficient vehicles.

5) However, the existing Vehicle Green Tax Plan is not the ideal platform to stimulate car users to switch over to low-emission and fuel-efficient vehicles. This plan sets a necessary fuel efficiency criterion as per the vehicle's weight classification. The fuel efficiency criterion for large vehicles is lower than that for small vehicles. Therefore, provided the stipulated criterion is achieved, this plan is applicable even to large vehicles. Thus, there is no strong incentives to purchase smaller more fuel-efficient vehicle.

and 9,590km in 2001 after the amendment.

In essence, although Japan has successfully established environmental policies to promote efficiency-improvement in passenger vehicles, a significant amount of energy is still used, and anticipated energy savings have not been achieved. To evaluate the actual effect of these environmental policies, it is necessary to estimate the rebound effect of the passenger vehicle transportation sector in Japan.

3 Direct Rebound Effect

Rebound effect is related to the consumers' tendency to consume more energy, an indirect consequence of the economic benefit from improved efficiency (Berkhout et al., 2000). For example, as a fuel-efficient car has better gas mileage than other types of cars, the cost per kilometer decreases, leading to increased consumption. As a result, a certain portion of expected energy savings is lost because people tend to consume more energy, if it is cheaper to do so. This phenomenon is known as the "rebound effect." This section shows the theoretical mechanism of the rebound effect, with particular emphasis on households.

3.1 The household production model

Following the household production model put forth by Becker (1965), we assume that individual households derive utility from consuming energy services (e.g., driving, air-conditioning, lighting, etc.). Let S_i is the i th energy service. We assume that S_i is produced by the production function f_i as follows:⁶⁾

$$S_i = f_i(E_i, k_i, o_i, t_i), \quad i = 1, \dots, n.$$

Here, E_i , k_i , o_i , t_i denote production factors, namely, energy, capital, other

6) This method was followed in appendix A of Sorrell and Dimitropoulos (2008), wherein they showed the various microeconomic considerations of the rebound effect.

market goods, and time, needed for producing the i th energy service S_i . Furthermore, we assume that household utility can be obtained from energy services as follows :

$$U = u(S_1, S_2, \dots, S_n), \quad \frac{\partial u}{\partial S_i} > 0, \quad \frac{\partial^2 u}{\partial S_i^2} < 0, \quad i = 1, \dots, n.$$

The available time budget of household T is divided into the hours spent on working t_W and the time necessary to produce services :

$$T = t_W + \sum_{i=1}^n t_i. \quad (1)$$

Note that t_W does not enter the utility function. Let w denote the wage rate. The budget constraints faced by the households is as follows :

$$w t_W = \sum_{i=1}^n (p_E E_i + p_k k_i + p_o o_i), \quad (2)$$

where, p_E and p_o indicate the prices of energy and other market goods, respectively, and p_k denotes the annualized capital cost required for service i . By combining time restrictions

(1) and budget constraint (2), Becker (1965) derived following total income M :

$$M := wT = \sum_{i=1}^n (p_E E_i + p_k k_i + p_o o_i + w t_i). \quad (3)$$

The total income M is the maximum labor income that a household could achieve if all the available time were to be spent working at wage rate w . The Lagrangian L for the utility maximization problem subject to budget constraint (3) is calculated as follows :

$$L := u(s_1, s_2, \dots, s_n) - \lambda \left[\sum_{i=1}^n (p_E E_i + p_k k_i + p_o o_i + w t_i) - M \right].$$

If joint production is ruled out, the first order condition of energy service j is given as follows :

$$\frac{\partial u}{\partial S_j} = \lambda \left[p_E \frac{\partial E_j}{\partial S_j} + p_k \frac{\partial k_j}{\partial S_j} + p_o \frac{\partial o_j}{\partial S_j} + w \frac{\partial t_j}{\partial S_j} \right]. \quad (4)$$

3.2 Introduction of energy efficiency

The typical definition of energy efficiency in energy economics literature is as follows :

$$\mu_i \equiv \lambda \frac{S_j}{E_j} > 0. \quad (5)$$

This implies that increased energy efficiency μ_j equals decreased energy consumption $E_j = S_j/\mu_j$ for the provision of a certain amount of j th energy service S_j . For example, in a motor vehicle, S_j and E_j denote the distance traveled and amount of gasoline consumed, respectively. The energy efficiency μ_j can be measured in terms of the kilometers traveled per liter. According to definition (5), the price of energy service per unit Ps_j becomes a decreasing function of energy efficiency μ_j , as shown bellow :

$$Ps_j = \frac{P_E}{\mu_j}. \quad (6)$$

In accordance with Becker (1965), households are, ultimately, not interested in the amount of energy E_j required for a certain amount of energy service S_j , but in the energy service itself.

In practice, more energy efficient appliances frequently have higher capital costs but simultaneously reduce operating costs through lower fuel and time requirements. However, it is generally assumed that energy efficiency μ_j and, hence, energy consumption E_j and the amount of j th energy service S_j are uncorrelated with all other input factors of the household production function such as capital k_j , other market goods o_j and time t_j . Based on this assumption, the relationship (6) and $\frac{\partial E_j}{\partial S_j} = \frac{1}{\mu_j}$,⁷⁾ the first order condition (4) can be simplified as

follows :

$$\frac{\partial u}{\partial S_j} = \lambda [Ps_j]. \quad (7)$$

In principle, this first order condition may be solved for S_j , since $\frac{\partial u}{\partial S_j}$ is invertible due to $\frac{\partial^2 u}{\partial S_j^2}$. Hence, the amount of j th energy service S_j is a function of energy service price Ps_j and total income M as follows :

$$S_j = g(Ps_j, M). \quad (8)$$

Based on this framework, we can prove the direct rebound effect of increased energy efficiency with respect to the j th energy service as follows: An improved energy efficiency, causing an increase in μ_j , will yield a decline in the per unit price of j th energy service Ps_j . If the j th energy service S_j is the usual kind (wherein the derived marginal utility from (7) is decreases as the demand increases), improved energy efficiency increases the μ_j and reduces per unit price of j th energy service S_j . As per the definition of the utility function, we can assume that a decrease in marginal utility will be accompanied by an increase in energy service demand. This is summarized as follows; households will usually demand more of the j th energy service S_j as it becomes cheaper through efficiency gains, thereby causing a rebound that partially offsets the potential energy savings due to the increased energy efficiency.

3.3 The direct rebound effect

RA rebound effect can be termed as an “unexpected result of energy efficiency improvement.” Based on definition (5), the direct rebound effect can be expressed as elasticity of energy service demand with respect to efficiency $\eta_\mu(S)$. Here, $\eta_\alpha(\beta)$

7) This relationship can be obtained by differentiating definition (5).

indicates an absolute value of elasticity, defined as $\eta_\alpha(\beta) = \frac{\partial \beta}{\partial \alpha} \frac{\alpha}{\beta}$. On differentiating energy consumption E_j in definition (5) with respect to energy efficiency μ_j , we get the following equation (j is abbreviated) :

$$\eta_\mu(E) = \eta_\mu(S) - 1. \quad (9)$$

The proof of the equation is as follows :

$$\eta_\mu(E) = \frac{\partial \ln E}{\partial \ln \mu} = \frac{\partial \ln S - \partial \ln \mu}{\partial \ln \mu} = \frac{\partial \ln S}{\partial \ln \mu} - \frac{\partial \ln \mu}{\partial \ln \mu} = \frac{\partial \ln E}{\partial \ln \mu} - 1 = \eta_\mu(S) - 1.$$

Here, $\eta_\mu(E)$ indicates the elasticity of energy demand with respect to energy efficiency. For example, if the elasticity of the kilometers traveled by the car with respect to fuel efficiency is 0.2 (i. e., $\eta_\mu(S) = 0.2$), then in accordance with equation (9), the elasticity of gasoline demand with respect to energy efficiency $\eta_\mu(E)$ would be 0.8. This implies that actual gasoline consumption decreases by only 8% even if the energy efficiency of the vehicle is improved by 10%. When $\eta_\mu(S) = 0$, the rebound effect disappears, and the energy savings by increased efficiency are achieved as expected.

In the following sections, using the definition of the direct rebound effect in (9) and the demand function in (8), we construct an econometric model and estimate the size of the direct rebound effect of vehicles owned by Japanese households.

4 Estimation of the direct rebound effect

As overviewed in section 2, although Japan has successfully implemented some environmental policies to promote increased fuel-efficiency in passenger vehicles, the anticipated fuel savings have not been realized. The rebound effect of passenger vehicles offsets the potential fuel savings accumulated through increased efficiency. Moreover, the achievement of the emission reduction targets through existing development and dissemination policies will be significantly delayed.

A number of empirical studies of the rebound effect have been conducted in the past (for example, Greene (1992), Greene et al. (1999), Roy (2000), Bentzen (2004), Small and Dender (2007), Jin (2007), etc.). However, such studies have been rare in Japan: examples include Washida (2006), Mizobuchi (2007), and Mizobuchi (forthcoming). Thus, there is a need for additional empirical evidence of the rebound effect for evaluation of Japanese fuel-efficiency policies.

This section aims to estimate the size of the direct rebound effect in the Japanese passenger vehicle sector using micro data and evaluates the actual effect of the existing environmental policies.

4.1 Econometric model

In our data, the corresponding data of the energy service S , energy efficiency μ and energy consumption E in definition (9) are annual travel distance ($km/year$), fuel efficiency (km/l) and the amount of gasoline consumption ($l/year$), respectively (see table 1, section 4.2). Following the definition of the direct rebound effect (9), we can estimate the size of the rebound effect by regressing the log of annual travel distance $\ln(km)$ on the log of fuel efficiency $\ln(\mu)$. From the demand function of equation (8), we can observe that the demand of the travel distance S depends on energy service $P_S (= P_E/\mu)$. Therefore, gasoline price data denoted by P_E is added to explanatory variables, as a control variable. Then, our econometric model is as follows :

$$\ln(km_i) = \beta_0 + \beta_1 \cdot \ln(\mu_i) + \beta_2 \cdot \ln(P_E, i) + \beta_{x_i} + \epsilon_i, \quad (10)$$

where the subscript i indicates the i th observation. ϵ_i indicates an unobserved disturbance term. The vector x_i denotes a set of household- and car-level variables.

It must be noted that the above econometric model includes fuel efficiency. For a car-owner, fuel efficiency can be determined by the expected distance to be

traveled. In this case, as the travel distance and fuel efficiency are decided simultaneously, the above econometric model (10) has an endogenous problem. Therefore, the OLS estimator is biased. To avoid this endogenous problem, we follow the models of Greene et al. (1999) and Small and Dender (2007) and reconstruct the econometric model as a simultaneous model, which is described as follows :

$$\ln(km_i) = \beta_0 + \beta_1 \ln(\mu_i) + \beta_2 \ln(P_{Ei}) + \beta_{X_i} + u_{1,i} \quad (11)$$

$$\ln(\mu_i) = \delta_0 + \delta_1 \ln(km_i) + \delta z_i + u_{2,i} \quad (12)$$

where z_i denotes the vector of explanatory variables that includes some factors related to fuel efficiency, and $u_{1,i}$ and $u_{2,i}$ represent the unobserved disturbance terms of equation 1 and equation 2, respectively.

4.2 Data

Most of our data was obtained from “CarSensor.net,” one of the famous used-car companies in Japan. This database includes information such as total travel distance, fuel efficiency, purchase price of the car, model year, riding capacity, engine size, weight of the car, type of fuel used, the drive system, with or without car navigation, with or without electronic toll collection (ETC), the selling area, etc.. From the 2007 database, we selected the cars with only one previous owner, and in the process narrowed down our sample size from 35512 to 2059 in a random manner.⁸⁾ The brands included in our dataset are “Toyota,” “Nissan,” “Honda,” “Subaru,” “Matuda,” “Suzuki,” “Mitsubishi,” “Daihatsu,” “BMW,” “VW,” and “Mercedes Benz.” The data on gasoline prices in each prefecture was obtained from “The Oil Information Center”.⁹⁾ Table 1 presents the data and standard statistics used in this study.¹⁰⁾

The average annual travel distance is approximately 6,300km/year; it is

Table 1. Data and statistics

Explanation of the data	Variable name	Mean	Standard error
Annual travel dis. (km/year)	km	6,300.5	4,078.8
Fuel efficiency (km/l)	μ	113.093	4.7667
Price of gasolin (yen/l)	PE	126.884	9.9717
Price of car (yen)	PCAR	319.09	246.97
Car age (year)	AGE	5.1034	2.3143
Riding capacity	CAPA	4.9859	1.2790
Engine size (cc)	CC	2,060.0	1,128.8
Car weight (kg)	WEIGHT	1,362.4	388.06
Kind of fuel (premium), [dummy]	HYOKU	0.4842	0.4999
4-wheel drive, [dummy]	4WD	0.2802	0.4492
Rear wheel, [dummy]	RD	0.2598	0.4387
Hybrid car, [dummy]	HYBRID	0.0311	0.1736
Car navigation, [dummy]	NAVI	0.4745	0.4995
ETC, [dummy]	ETC	0.1977	0.3983
Hokkaido, [dummy]	NORTH	0.1000	0.3001
Vehicle Green Tax Plan, [dummy]	GREEN	0.3798	0.4855

calculated by dividing the total travel distance by the age of the car.¹¹⁾ Similarly, the price of gasoline is also the average of gasoline prices across the years from the model year to 2008, when it is approximately 126.9 yen/l. The rest of the data remains constant through time, and, therefore, is listed without modification. The dummy variables are “kind of fuel,” “drive system (4WD, RD),” “hybrid,” “NAVI,” “ETC,” “Hokkaido,” and “Vehicle Green Tax.” The average values of these dummy variables indicate their share of the sample. For example, the average value of NAVI is 0.4745, which implies that approximately 47% of the sample cars are equipped with a navigation system.

8) Between July 10, 2007 and October 23, 2007, every time data was updated on the website of “Car Sensor.net”, the additional data was incorporated in our database.

9) The complete dataset used in this study is available request. URL : <http://oil-info.ieej.or.jp/index.html>

10) We have taken the average for all data over the time period, and hence, data is cross section data.

11) The datafor “car age” is calculated by subtracting model year from 2008.

It must be noted that the car navigation system and the ETC tend to prolong the drive. Moreover, most of northern Japan (Hokkaido prefecture) is rural. Hence, people in Hokkaido use cars more frequently on a daily basis and travel relatively longer distances. To confirm the fact, we introduce the “NAVI,” “ETC,” and “Hokkaido” dummies in the independent variables.

We also introduced household variables, such as income level, the number of members in the household, and environmental awareness, in the econometric model. Unfortunately, the database does not include these variables. We have also used three proxy variables such as the purchase price of car, riding capacity, and the dummy variable “GREEN,” as the data for these was not available. The dummy variable GREEN denotes the vehicles that are targeted by the government’s Vehicle Green Tax Plan. The owners of such vehicles may have high environmental awareness as they purchased cars that are both low emission and fuel efficient even though these cars are more expensive or reductions in motor vehicle tax and automobile acquisition tax are only two years.¹²⁾ Thus, using this dummy variable, we also investigate the impact of high environmental awareness on the rebound size using the following econometric analysis.

The included variables of x_i and z_i in the simultaneous equation model (11)–(12) are as follows :

$$\begin{aligned} x_i &= \{P_{CAR}, PCAR, AGE, CAPA, HYOKU, NAVI, ETC, \\ &\quad \text{NORTH, GREEN}\}, \quad (13) \\ z_i &= \{P_E, CC, WEIGHT, 4WD, RD, HYBRID, HYOKU, GREEN\}, \end{aligned}$$

In our estimation, we take the logarithm in km , μ , P_E , P_{CAR} , CC and

12) The owners of hybrid vehicle, natural gas vehicle, and methanol vehicle paid a lot of money for purchasing their vehicles, but they can be given preferential treatment of “Vehicle Green Tax Plan” semipermanently. On the other hands, the fuel-efficient vehicles are inexpensive, but the length of the preferential treatments are only two years.

WEIGHT.

5 Estimation results

5.1 Full sample estimation

The data on fuel efficiency μ used in this paper is theoretical and not observed. Moreover, we assume that drivers are able to achieve the theoretical fuel efficiency. Using the generalized method of moments (GMM) of Hansen (1982), we estimate our simultaneous equation model (11)–(12). Table 2 shows these results. For comparison, we also show the results of OLS estimation.

We use the dummy variables, “drive system (MT, AT, and CVT),” “fixing experience,” and “manufacturer,” as instrumental variables in the GMM estimation. Because the pvalue of the J-statistics is 0.2237, the null hypothesis—excess instrumental variables are effective—is not rejected. Therefore, we can confirm that the econometric model (11)–(12) is statistically supported. In addition, the adjusted R-squares of each equation (travel distance equation (11) and fuel efficiency equation (12)) are 0.09 and 0.69, respectively. Due to the small sample size, the R-square of equation (11) is slightly small. Further, the value of R-square derived by Greene et al. (1999) is also small (approximately 0.29) as compared to that of equation (12). Lastly, on comparing the results of the GMM and OLS estimations, we confirm the influence of the endogeneity of the fuel efficiency and travel distance km.

The estimated coefficient of fuel efficiency μ denotes the size of the rebound effect. Based on table 2, we estimated the rebound effect of passenger vehicles to be about 22%. This implies that the potential energy savings expected by engineers will be reduced by approximately 22% and actual savings are reduced to 78%. We compare our results with the results of some previous works on this subject. Greene et al. (1999) estimated the rebound effect of American passenger vehicles to

Table 2 . Estimation results (full sample)

equation (11)	(travel distance)	
variable	GMM	OLS
$\ln(\mu)$	0.2233**	0.2168*
$\ln(P_E)$	-2.0090***	-1.9972***
$\ln(P_{CAR})$	-0.0972**	-0.0439
AGE	0.0004	0.0163**
CAPA	0.0985***	0.0818***
HYOKU	0.2392***	0.1893***
NAVI	0.1320***	0.1303***
ETC	0.1184***	0.1585***
NORTH	0.1687***	0.1799***
GREEN	-0.0582**	-0.0498
const	17.5687***	17.2395***
adjust-R ²	0.0879	0.0926
equation(12)	(fuel efficiency)	
$\ln(km)$	0.1935***	0.0164***
$\ln(P_E)$	0.8193***	0.4042***
CC	0.0009	-0.2140***
WEIGHT	-0.8269***	-0.3099***
4WD	-0.0459***	-0.0937***
RD	-0.1100***	-0.1216***
HYBRID	0.6507***	0.6317***
HYOKU	-0.1359***	-0.1319***
GREEN	0.0731***	0.0637***
const	2.8691***	4.3110***
adjust-R ²	0.6876	0.8566
Observation	2,059	2,059

, * and **** denote significance at $p < 0.10$, $p < 0.05$ and $p < 0.01$, respectively.

be approximately 22%. Similarly, Small and Dender (2007) estimated the short-term and long-term rebound effects of American passenger vehicles, using long-term panel data to be about 4.5% and 22.2%, respectively. Thus, we can say that our estimation is consistent with those of the abovementioned studies. However, the estimated rebound effect of German passenger vehicles, estimated by Frondel et al. (2007) to be about 56%–66%, differed considerably from our estimation of 22%.

These differences might be the consequences of the varied consumption characteristics and patterns observed in different countries and sectors. However, one possible reason for this difference is that the former two works conducted the estimation using the simultaneous equation model while considering the endogenous problem, whereas the latter study was estimated using only the single equation of travel distance. Therefore, the rebound effect of Frondel et al. (2007) may have bias.

In our results, the estimated coefficients of both NAVI and ETC are positive and statistically significant. Hence, we conclude that car navigation systems and electronic toll collection systems do promote vehicle usage. The coefficient of NORTH is positive and statistically significant. Therefore, people living in Hokkaido, which has a larger area, are likely to drive longer distances. Moreover, as the elasticity of energy price " P_E " has a large negative value (-2.01), we can state that the introduction of environmental tax is effective in reducing fuel consumption. The estimated results of the second equation show that the coefficients of travel distance (km) and fuel price (P_E) are positive and statistically significant. This indicates that increases in expected travel distance and fuel prices induce people to buy fuel-efficient cars.

Lastly, in equation (11), we can find that the coefficient of GREEN was estimated to be positive and statistically significant. This shows that environmental awareness leads to reduced fuel consumption. In the next subsection, we confirm and analyze the manner in which environmental awareness impacts the rebound size.

5.2 High environmental awareness vs. low environmental awareness

This paper also aims to investigate the effect of environmental awareness on the rebound size. To study this, we divide the sample into the following two groups : (i) the high environmental awareness group ($n=782$) and (ii) the low

Table 3 . Estimation results (two groups) : with GMM estimation

equation (11)	(travel distance)	
	(i) high environmental	(ii) low environmental
variable	awareness	awareness
$\ln(\mu)$	0.1662	0.4109***
$\ln(P_E)$	-2.4515***	-1.7263***
$\ln(P_{CAR})$	0.2196***	-0.4052***
AGE	0.0269*	-0.0148**
CAPA	0.0596***	0.0732***
HYOKU	0.0714	0.2047***
NAVI	0.0728	0.0931***
ETC	0.0613	0.0821***
NORTH	0.0982	0.1091**
const	18.2780***	19.7371***
adjust-R ²	0.0916	0.0526
Observation	782	1277

***, ** and * denote significance at $p < 0.01$, $p < 0.05$ and $p < 0.10$, respectively.

environmental awareness group ($n=1277$). This division is based on whether or not the car is targeted by the government's Vehicle Green Tax Plan. Using the same model (11)–(12) and the same estimation method, we estimated the rebound effect for each group; table 3 presents the results. However, in this case we have excluded the OLS estimation results and the estimation results of equation (12) in order to conduct a simple comparison between the two groups.

The R-square values for both groups are similar to that of the full sample. Moreover, as both the J-tests are accepted, we conclude that both the models are supported statistically. Using the estimated coefficient of fuel efficiency- μ -for both the groups, we confirm the clear disparity between the two groups. The rebound effect of the high environmental awareness group was positive but statistically insignificant. This shows that this group has minimal or no rebound effect. On the other hand, the rebound effect of the low environmental awareness group was

positive and statistically significant. Moreover, the size of the rebound for this group (41%) was larger than that for the entire sample (22%). This shows that as environmental awareness increases, rebound effect decreases. Thus, we conclude that in order to achieve the targeted energy savings, the Japanese government should implement policies to raise people's awareness of the environment.

6 Conclusion

This paper analyzed the size of the rebound effect of passenger vehicles in Japan on the basis of the definition of the direct rebound effect and the household production model. The rebound effect was estimated to be about 22% for the entire sample. Further, on dividing the sample into two groups, the high and low environmental awareness groups, we also analyzed the effect of environmental awareness on the rebound size. For the high environmental awareness group, the rebound effect was statistically insignificant, whereas for the low environmental awareness group, it was estimated to be approximately 41%, which was larger than that for the full sample. Thus we conclude that increased environmental awareness decreases the rebound size.

The rebound effect of passenger vehicles in Japan was less than 100%. Hence, we can say that energy-saving and efficiency-improvement policies have decreased fuel consumption. However, the size of the rebound effect is not negligible, and it negates a significant portion of the potential energy savings. Therefore, the Japanese government should consider implementing additional environmental policies to decrease the size of the rebound effect. From our paper, we derive the conclusion that raising people's environmental awareness is an effective measure to address the rebound effect.

We conclude that rebound effect is a good measure of the effectiveness of the

energyefficiency improvement policy. The Japanese government has intensified the promotion of energy-efficiency improvement policies since the publication of the Kyoto Protocol. The Japan government supports various energy-efficiency improvement projects in various sectors including industry, construction, transportation, and household, and it is thus necessary that the Japanese government take into consideration the rebound effect in order to accurately measure the effectiveness of its energy-efficiency improvement policies.

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