Assessing the Fuel Use and Greenhouse Gas Emissions of Future Light-Duty Vehicles in Japan

by

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Bachelor of Engineering in Mechanical Engineering
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Submitted to the Engineering System Division
in partial fulfillment of the requirements for the degree of

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ABSTRACT

Reducing greenhouse gas (GHG) emissions is of great concern in Japan, as well as elsewhere, such as in the U.S. and EU. More than 20% of GHG emissions in Japan come from the transportation sector, and a more than 70% reduction in GHG emissions by 2050 has been projected as a feasible goal. It is clear that substantial reduction in GHG emissions from the transportation sector will be required in Japan over the next several decades.

This research developed a fleet model for Japan to evaluate GHG emission trends through 2030 and through 2050. The fleet model shows that GHG emissions from light-duty vehicles are likely to decrease significantly due to anticipated decrease of vehicle kilometers traveled (VKT) from all the light-duty vehicles in Japan over the next several decades. This is because of several factors, such as the decrease of vehicle sales due to the recession and higher gasoline prices.

In the analysis through 2030, the fleet model was run under four "sales mix scenarios," including a scenario which is based on the forecast by the Japanese Government. Even in the scenario without any sales mix change in the future, a 36% GHG emission reduction from the level of 2008 is achieved by 2030. In the Government Scenario (the most optimistic scenario), a 49% GHG emission reduction from the level of 2008 is achieved by 2030.

In the longer-term analysis through 2050, the fleet model was run under two "sales mix scenarios" and two "vehicle fuel consumption forecasts." In the most conservative case, a 54% GHG emission reduction from the level of 2008 is achieved by 2050. In the most optimistic case, a 67% GHG emission reduction from the level of 2008 is achieved by 2050.

Even though substantial GHG emission reductions by 2050 are projected, coordinated policy measures would make the most optimistic sales mix scenario more feasible, and help realize further GHG emission reductions.

Thesis Supervisor: John B. Heywood
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1. INTRODUCTION

1.1 Objectives

The overall objective of this research is to quantify the potential future petroleum, energy and environmental impacts of the new and improved technologies and fuels likely to be developed and deployed in light-duty vehicles.

Under the Kyoto Protocol, which was initially adopted on 11 December 1997 in Kyoto, Japan, and entered into force on 16 February 2005, Japan committed to reducing greenhouse gas (GHG) emissions by 6% from the 1990 level during the period between 2008 and 2012. This constituted a very stringent target for Japan because GHG emissions have already increased after 1990. The percentages of GHG emission increase by 2005 from the level of 1990 are 44.6% from the commercial and other sectors, 36.7% from the residential sector, and 18.1% from the transportation sector [Matsuhashi et al., 2007].

Over the next several decades, substantial reduction in GHG emissions from the transportation sector will be required. The share of GHG emissions from the transportation sector in Japan was 24.4% in 2008 [IEA, 2008]. In particular, more than 80% of GHG emissions of the transportation sector in Japan were derived from vehicles such as passenger cars and trucks in 2006 [Public Relations Division of MLIT, 2008]. As Japan as well as other countries in the world consider how best to set targets for reducing GHG emissions, assessing the opportunities for reducing the transportation sector's contribution is especially important.

The Japanese government has addressed these issues in five main ways [MLIT, 2007]. First, the Japanese government has been promoting popularization of "environmentally friendly vehicles" such as hybrid and battery electric vehicles. Due to the great efforts by the government, the sales of hybrid vehicles have been growing rapidly over the last several years. Second, the government has set stringent targets for fuel economy based on the best available technology. Third, the government has been working on constructing an "efficient transportation system." Fourth, the government has been trying to introduce "efficient traffic control" and develop infrastructure. Fifth, the government has promoted the use of public transport, such as trains and buses, instead of passenger cars. Since the high gasoline prices (about JPY 150 per liter [The Oil Information Center, IEEJ, 2011]) for the last several years have also helped this government policy a great deal, people drive less than they did previously.

Owing to these integrated approaches by the Japanese government, GHG emissions from vehicles have gradually started decreasing. However, it is still unclear what the fleet impacts will be in the future. Therefore, the purpose of my research is to forecast and analyze fuel use and GHG emissions from light-duty vehicles (LDVs: passenger cars and light trucks) in Japan over the next few decades. The analysis is divided into two parts: near future (through 2030) and longer term (2030-2050). In the first part, the results from the fleet model are based on detailed assumptions. In the second part, the results from the fleet model have more uncertainties, but it is useful to have a rough image of GHG emission trends as long-term targets for GHG reductions are considered.

1.2 Overview of Transport in Japan

Japan is a small-size country and the land area is 378 thousand km^2, which is about 4% of that of the United States [Statistics Bureau of MIAC, 2010]. However, the population is 128 million, more than 40% of that of the United States [Statistics Bureau of MIAC, 2010]. Because of these differences, the characteristics of transport are quite different from those of the United States.

The number of kilometers-traveled per person per year is given in Figure 1 [Transport Research and Statistics Office, MLIT, 2010]. The demand for railroad is quite high because the modern network of railroads spreads over the whole country including a high speed railroad called *Shinkansen*. On the other hand, the demand for air transport is relatively low, arguably because of the existence of the high speed railroad and of the small land area. The kilometers-traveled per person by passenger car increased at an annual rate of 2.6% in 1990s, but has recently been decreasing. On the other hand, the kilometers-traveled per person by railroad has gradually been increasing. There are at least three possible reasons for this trend. First, the price of gasoline was high in the latter half of the past decade. Second, the network of railroads has been extending, and the railroad is becoming more convenient for traveling. Third, more and more people are interested in climate change issues. Yet even though people are less dependent on vehicles for traveling in Japan compared with the United States, in 2006 more than 80% of transportation GHG emissions came from road vehicles, including buses and trucks [Public Relations Division, MLIT, 2008].

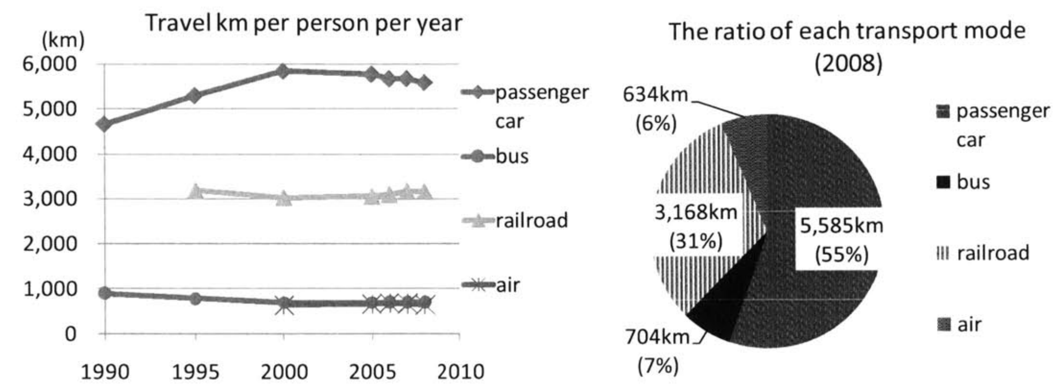


Figure 1. The kilometers-traveled per person per year of each transportation model [Transport Research and Statistics Office, MLIT, 2010]

It is therefore appropriate to focus on the road transportation. The categorization of Japanese vehicles, shown in Table 1, is unique. There are three vehicle categories for passenger cars, and three vehicle categories for trucks. For passenger cars, vehicles are categorized based on the size and displacement. First come "K-cars," so called because the pronunciation of K stands for "light" in Japanese. As for trucks, vehicles are categorized based on the size, displacement, and load capacity. The scope of this research is limited to LDVs. That means the first five categories shown in Table 1, and does not include "normal trucks." Normal trucks are excluded for the following reasons. First, most of the normal trucks are heavy-duty vehicles, which are mainly used not for personal transport but for freight. Second, diesel oil is used for normal trucks in most cases, which is completely different from the trend of light-duty vehicles, which use gasoline in most cases.

Table 1. Japanese vehicle categories

Vehicle category		Definition	Vehicle stock (2009)	Vehicle sales (2009)
passenger cars	K-car (light motor vehicle)	Maximum length: 3.4m Maximum width: 1.48m Maximum height: 2.0m Maximum displacement: 660cc	17.5 million	1.3 million
	compact car	Maximum length: 4.7m Maximum width: 1.7m Maximum height: 2.0m Maximum displacement: 2000cc	23.7 million	1.6 million
	normal car	All passenger cars other than above	16.7 million	1.3 million
trucks	K-truck (light truck)	Maximum length: 3.4m Maximum width: 1.48m Maximum height: 2.0m Maximum displacement: 660cc Maximum load capacity: 350kg	9.2 million	0.4 million
	compact truck	Maximum length: 4.7m Maximum width: 1.7m Maximum height: 2.0m Maximum displacement: 2000cc (except for Diesel and CNG) Maximum load capacity: 2000~3000kg (ambiguous)	3.9 million	0.2 million
	normal truck	All trucks other than above	2.3 million	0.1 million

2. FLEET MODEL DEVELOPMENT (through 2030)

2.1 Fleet Model Overview

A quantitative model for assessing the impacts on Japan's GHG emissions of different evolving transportation technologies and fuel scenarios needs the following components: [Heywood, 2010]

(a) A vehicle analysis capability that, for given propulsion system and vehicle technologies, can predict the vehicle's fuel consumption and GHG emissions over specified drive cycles.

(b) A model for the dynamics of the in-use vehicle fleet, which includes vehicle sales and scrappage rates, and annual kilometers traveled.

(c) Specification of new or improved technology introduction timeframes and deployment rates of these technologies as a function of time.

(d) The resolution of the vehicle fuel consumption, performance, and vehicle size trade-off that, for given powertrain and vehicle technologies, affects the improvement in fuel consumption actually achieved.

(e) Quantitative scenarios for the fuel (or energy) streams expected to be available over the appropriate timeframe and the GHG emissions associated with the production and distribution of those fuels.

MIT's Sloan Automotive Laboratory has developed such a methodology for the respective LDV fleets for the United States context [Bandivadekar et al., 2008] and for several major European countries [Bodek and Heywood, 2008]. There is also a similar study by Greene and Plotkin for the U.S. transportation sector [Greene and Plotkin, 2011]. Based on the MIT work, the overall structure of the in-use LDV fleet model is given in Figure 2, which shows the required inputs, and the logical sequence of the outputs: the make-up of the LDV stock; the LDV fleet kilometers traveled; the fleet fuel use; and the fleet GHG emissions. The fleet model is composed of several worksheets in Microsoft Excel. The several components of this methodology will now be reviewed.

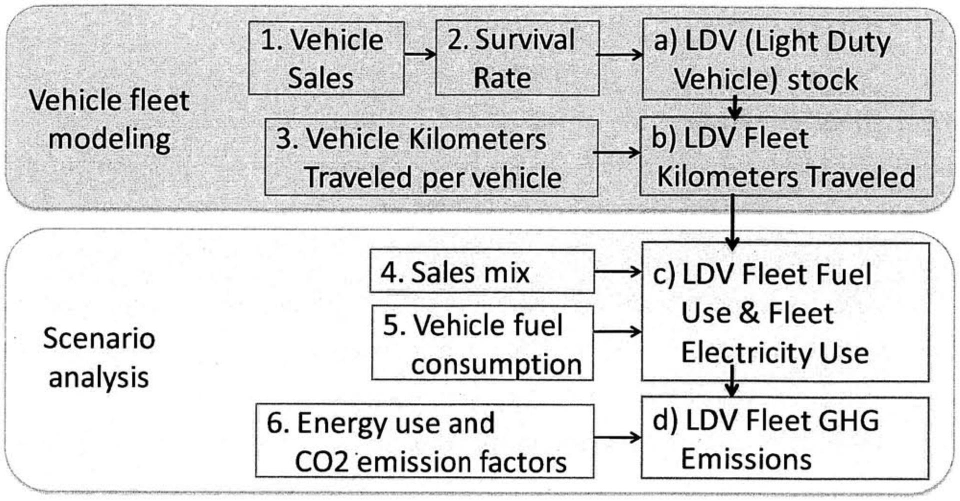


Figure 2. Fleet model overview

2.2 Key Assumptions

Not only historical data but also several other assumptions are required to operate the fleet model. These assumptions, which are described in detail below, include the future growth rate of new vehicle sales, the fuel consumption of new vehicles, and the VKT behavior.

2.2.1 Timeframe (near future: through 2030)

A two-decade timeframe through 2030 was chosen over which to evaluate the results from the fleet model. The timeframe was capped at twenty years because it is very difficult to project improvements in various factors beyond this period. Since analyzing beyond this period involves more uncertainties, near-future analysis is separated from longer-term analysis.

2.2.2 Sales Projection

The annual sales of LDVs in Japan from 1975-2009[1] are shown in Figure 3. Here, I considered the number of newly registered vehicles as the number of sales.

1 Throughout this report, the years cited are fiscal years (April 1 to March 31)

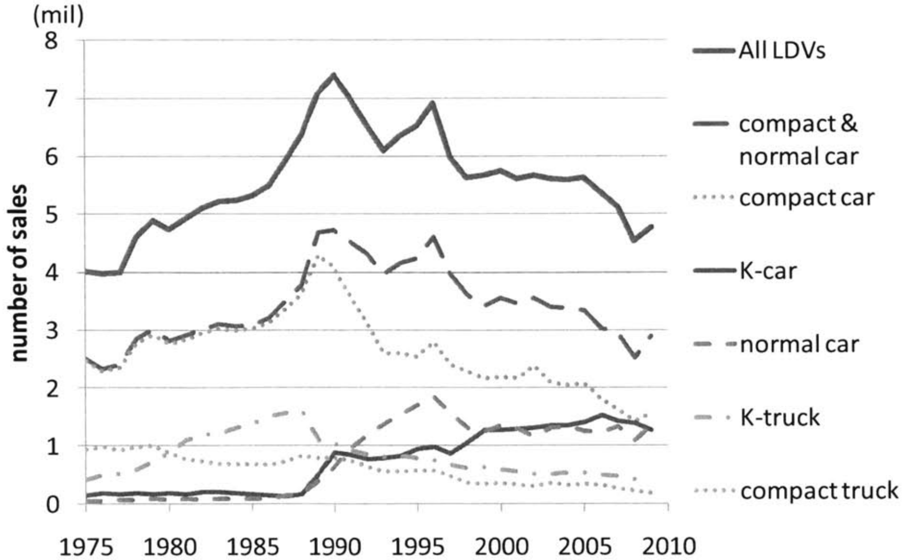


Figure 3. Vehicle sales in Japan
[AIRIA, 2000, 2009]

The number of LDV sales increased significantly in the 1980s, and the number of total LDV sales was larger than seven million around 1990. However, the number of sales has recently been decreasing in all the vehicle categories except for K-cars. Since the vehicle sales have been decreasing so rapidly, the future vehicle sales trend is projected and shown in both Table 2 and Figure 4, based not on historical data but on the government's sales forecast. More concrete reasons for choosing this approach are as follows. First, if vehicle sales are forecast based on historical data, the sales of compact trucks becomes close to zero in a few years, which is not plausible. Therefore, the decreasing trends of vehicle sales should be leveling off. Second, the sales peak around 1990 was due to the bubble, and the rapid decrease trends in the late 2000s were due to economic recessions. Thus, the historical data do not necessarily seem to be good sources for the future sales forecast.

Table 2. Vehicle sales growth projection (growth % per year)

	K-car	compact &normal car	K-truck	compact truck
2010~2020	1.0%	-0.2%	1.0%	-0.9%
2020~2030	-0.2%	-0.4%	-0.2%	-0.7%

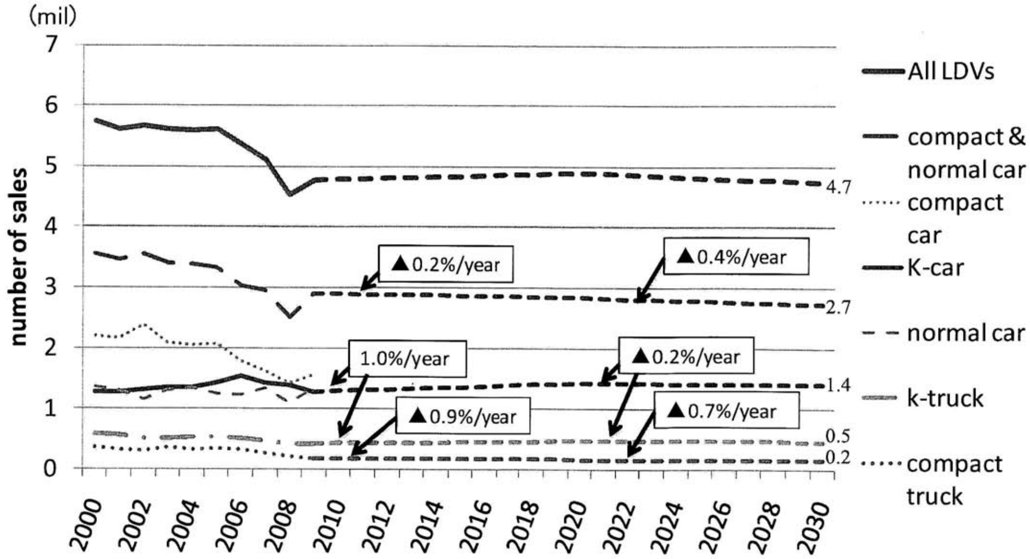


Figure 4. Vehicle sales projection in Japan

2.2.3 Survival Rate

The survival rates of compact and normal passenger cars in the years between 1999 and 2008 are shown in Figure 5, and the survival rates of compact trucks in the years between 1999 and 2008 are shown in Figure 6. The survival rate curve shifts from the left to the right as the data becomes more recent in compact and normal passenger cars. On the other hand, the survival rate curve does not always shift to the right as the data becomes more recent in compact trucks.

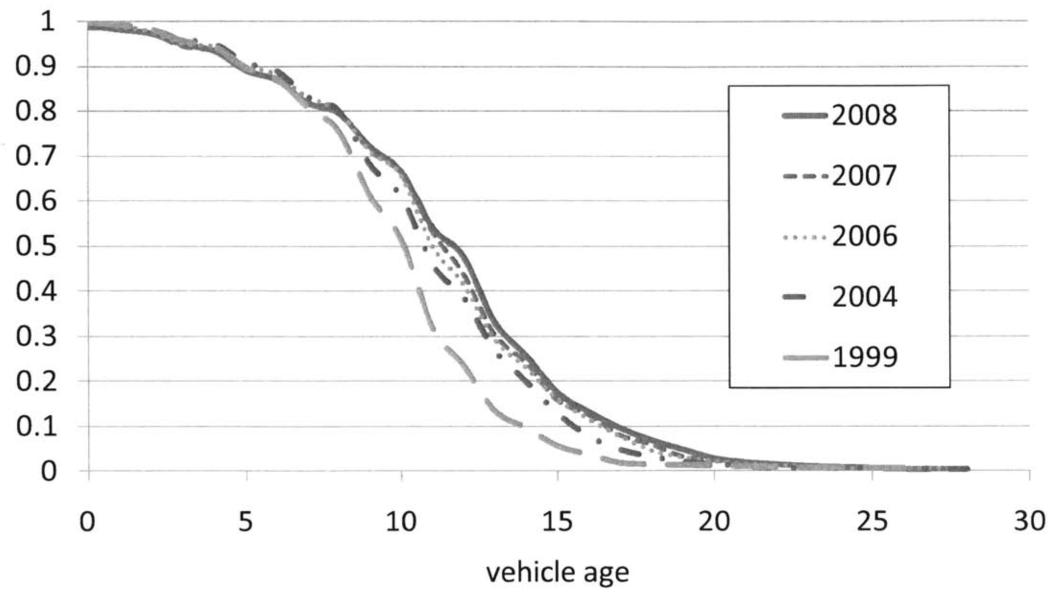


Figure 5. The survival rates of compact and normal passenger cars
[AIRIA, 2000, 2005, 2007, 2008 and 2009]

Figure 6. The survival rates of compact trucks
[AIRIA, 2000, 2005, and 2009]

There are two problems. First, there is considerable uncertainty about the survival rates of motor vehicles. Second, no consistent data on survival of vehicles of different model years is available. In the literature, three different methodologies have been used to estimate vehicle scrappage rates: (1) a logistic function to estimate the survival rate of light-duty vehicles based on the median lifetime of cars and light trucks [Greene and Chen, 1981]; (2) a Weibull distribution based on attrition rates of passenger cars [Libertiny, 1993]; (3) quantifying engineering scrappage, defined as scrappage resulting from vehicle aging and accompanying physical wear and tear [Greenspan and Cohen, 1999].

For the purpose of our model, the survival rate of new vehicles is determined by using a logistic curve as shown in Equation 1.

$$r(t) = 1 - \frac{1}{\alpha + e^{-\beta(t-t_0)}} \quad (1)$$

where *r(t)* is the survival rate of vehicle at age *t*; t_0 is the median lifetime of the corresponding model year; *t*, the age in a given year; β, a growth parameter defining how fast vehicles are retired around t_0; and α, a model parameter set to 1. Therefore, we need the median lifetime (t_0) and a growth parameter (β).

2.2.3.1 Median lifetime

Since there is no data of median lifetime, which will be used for the logistic curve of the survival rate function, it has to be assumed based on the average lifetime. The trend of average lifetime is shown in Figure 7.

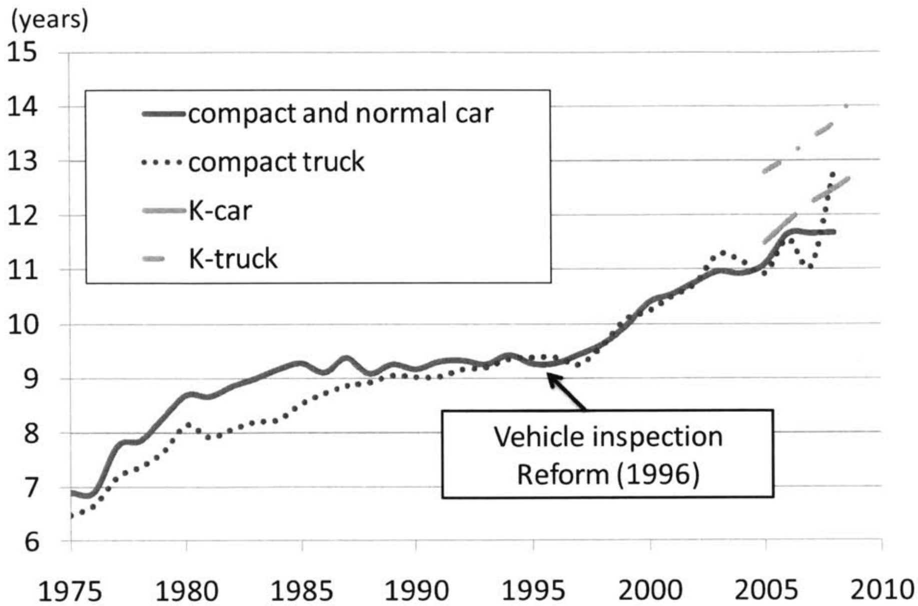


Figure 7. The trend of average lifetime Japan
[MLIT, 2009; LMVIO, 2010]

The average lifetime of vehicles starts growing rapidly after 1996. This must be related to the vehicle inspection reform in 1996. Because of the vehicle inspection reform, the vehicle inspection intervals for compact and normal passenger cars of vehicle age ten and over were extended from every year to every two years.

Vehicle inspection cost, shown in Table 3 [Road Transport Bureau, MLIT, 2011; NAVI, 2011; LMVIO, 2005], is very high in Japan, and is a heavy financial burden on drivers. Therefore, this is probably the reason for rapid average lifetime growth of about 1.7% per year after 1997.

Table 3. Vehicle inspection cost
[Road Transport Bureau, MLIT, 2011; NAVI, 2011; LMVIO, 2005]

		K-cars/trucks	Compact/normal cars	Compact trucks
Mandatory cost	Vehicle weight tax (for 2 years)	JPY 7,600	JPY 10,000~60,000 (Depending on vehicle weight)	JPY 7,600~80,000 (Depending on vehicle weight)
	Vehicle insurance (2 years)	JPY 21,970 (2011.4~)	JPY 24,950 (2011.4~)	JPY 23,130 (2011.4~)
	Service charge	JPY 1,100~1,400	JPY 1,100~1,800	JPY 1,100~1,800
Extra cost	Maintenance cost	Depending on conditions		

The trend of median lifetime, which is obtained based on the trend of average lifetime, is shown in Figure 8. The following methods are used in order to get the trend of median lifetime. First, the linear fit of average lifetime for each kind of vehicle is obtained. Second, the median lifetime is calculated by adding some adjustments to the average lifetime. The adjustments, which are shown in Table 4, are introduced so as to make the fleet model result for vehicle stock closer to the vehicle stock data [AIRIA, 2009]. Third, the future growth of median lifetime is forecast based both on the historical growth and on the government's lifetime prediction, which is shown in Figure 8 and Table 5.

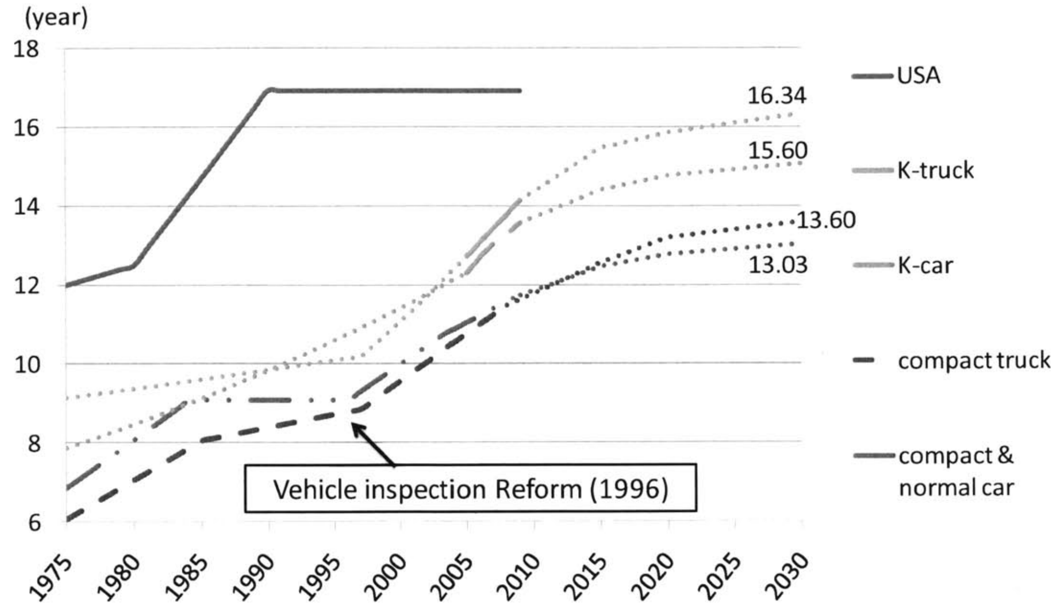


Figure 8. The trend of median lifetime

Table 4. Adjustments for median lifetime

	Adjustments
K-cars	0.8
Compact and normal passenger cars	-0.2
K-trucks	0
Compact trucks	-0.5

Table 5. The growth projections for median lifetime

	K-car	Compact and normal car	K-truck	Compact truck
2010~2015	1.0%	1.0%	1.5%	1.3%
2015~2020	0.5%	0.5%	0.5%	1.0%
2020~2030	0.2%	0.2%	0.3%	0.3%

2.2.3.2 Growth parameter

As shown in Figures 5 and 6, the survival rates of compact and normal passenger cars, and those of compact trucks, are available for some years. Therefore, the growth parameter β is obtained by comparing the raw data of survival rate and the survival rate using the logistic function. In comparing the raw data of survival rate and the survival rate as a logistic function, I calculated β by using the least squares method. One example of the comparison (survival rate of compact and normal passenger cars in 2008) is shown in Figure 9.

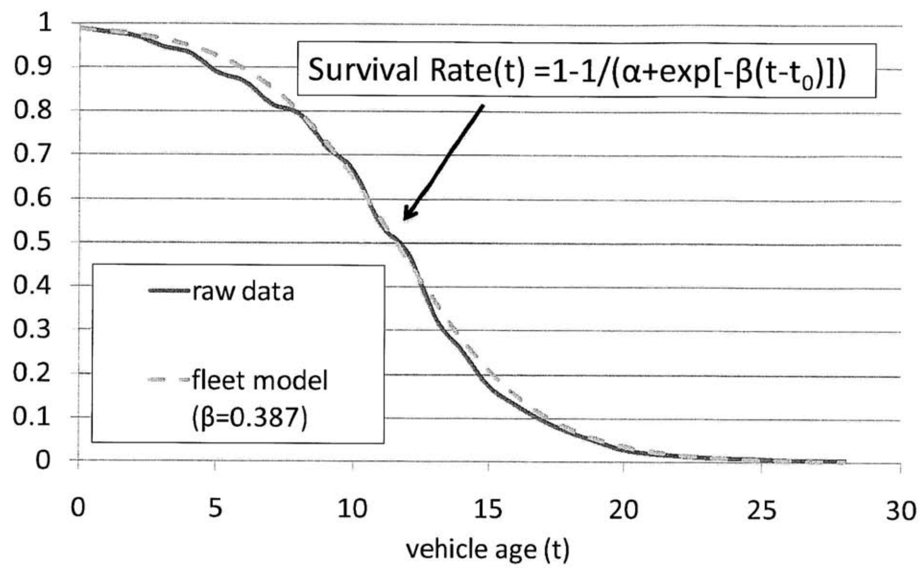


Figure 9. The comparison of survival rate curves

In this way, I obtained a β which is different from those of other years. As for the survival rate between 1999 and 2008, it seems that there is a linear correlation between β and the year, which is shown in Figure 10. Therefore, I changed β according to the year between 1999 and 2008. Since I do not have the actual data of survival rate of any year before 1999 and after 2008, β is kept constant for any year before 1999 and after 2008. There are two reasons for this. First, β would be below 0 or close to 1 at some point if this linear correlation between β and the year were to continue before 1999 and after 2008. Second, in the U.S. case, β is kept constant for any year. (In the U.S., β=0.28 for cars, β=0.22 for trucks.) Based on these considerations, β=0.54~0.39 for compact and normal passenger cars, and β=0.41~0.27 for compact trucks in Japan. β is set to be 0.39 for K-cars and 0.27 for K-trucks for any year because there is no data available about K-cars and K-trucks.

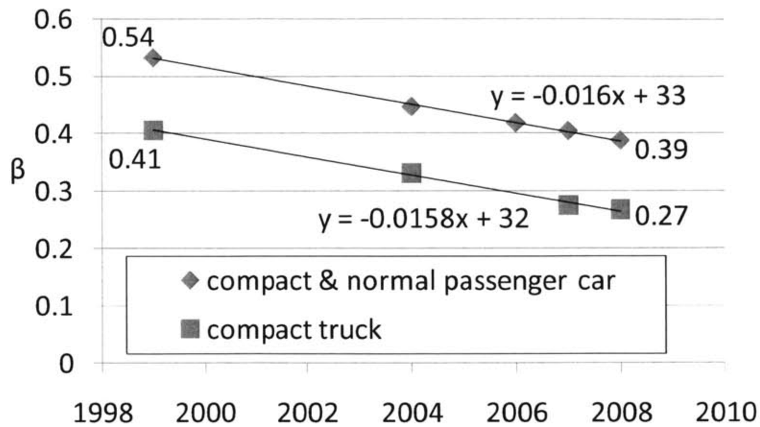


Figure 10. Growth parameter β for different years

2.2.4 Vehicle Kilometers Traveled (VKT)

The VKT behavior has important effects on future fleet fuel use and GHG emissions. The trend of VKT per vehicle per year for each type of vehicle except for compact trucks is shown in Figure 11 (no data are available for compact trucks.) The historical VKT per vehicle data highlight several important trends. First, the trends are completely different for different vehicle categories. More specifically, though the VKT per vehicle for compact and normal passenger cars has been decreasing, that for K-cars and K-trucks has been increasing. Second, the VKT per vehicle for compact and normal passenger cars has been much larger than that for K-cars in any year before 2009.

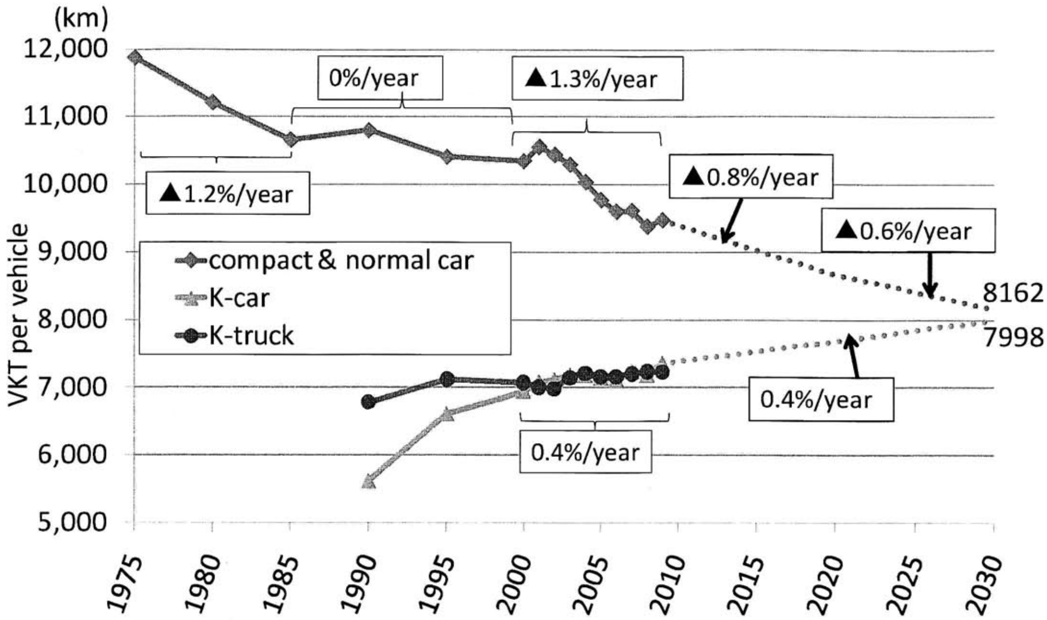


Figure 11. VKT per vehicle per year
[Transport Research and Statistics Office, MLIT, 2010]

The growth in VKT per vehicle for K-cars is 0.4% per year between 2000 and 2009. In addition, VKT per vehicle for K-trucks has a similar trend between 2000 and 2009. Therefore, the rate of growth in VKT per vehicle for K-cars and K-trucks is assumed to be 0.4% per year through 2030, taking into consideration historical VKT growth and government projections.

On the other hand, the growth in VKT per vehicle for compact and normal passenger cars is -1.2% per year between 1975 and 1985, 0% per year between 1985 and 2000, and -1.3% per year between 2000 and 2009. Therefore, the rate of growth in VKT per vehicle for compact and normal passenger cars is assumed to be -0.8% per year through 2020, and -0.6% per year between 2020 and 2030, taking into consideration historical VKT growth and government projections. In the present research, the rate of growth in VKT per vehicle for compact trucks is assumed to be the same as that of compact and normal passenger cars, because the growth trends of K-cars and K-trucks are similar.

It is assumed that new compact and normal passenger cars are driven 12,700km in their first year, which is calculated based on the cumulative VKT per vehicle data in 2009 [Road Transport Bureau, MLIT, 2010]. After the first year, the VKT per vehicle decreases at an annual rate (denoted r) of 6.5% for compact and normal passenger cars and 6.2% for K-cars as vehicles get older. This number is obtained by calculation using the least squares method. Thus, the VKT per vehicle of a vehicle aged i years is calculated as:

$$VKT_i = VKT_{new} \times e^{-ri}$$

Based on Figure 11 and this equation, the vehicle kilometers traveled by compact and normal passenger cars of different ages can be calculated. Figure 12 shows the annual distance traveled by the new compact and normal passenger cars at 5-year intervals between 1980 and 2005, and in 2009.

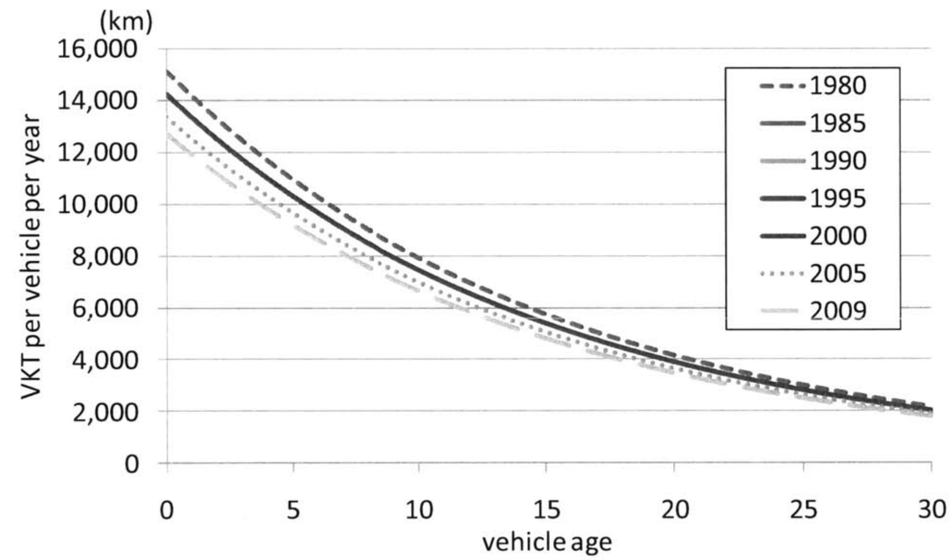


Figure 12. VKT per vehicle per year by model year (1980-2009)

In the same way, r is set to 0.062 (6.2%) for K-cars. Since no cumulative VKT per vehicle data for trucks is available, r=0.065 (6.5%) is used for compact trucks, and r=0.062 (6.2%) is used for K-trucks.

The total VKT for a given calendar year, j, is obtained using the following equation:

$$VKT_j = \sum_i N_{i,j} * VKT_{i,j}$$

where $N_{i,j}$ is the number of vehicles of age i in calendar year j, and $VKT_{i,j}$ is the average annual vehicle travel for vehicles of age i in year j.

2.2.5 Future Sales Mix Scenarios

Different scenarios are used to project the fuel use of light-duty vehicles under different market and policy conditions. These scenarios also allow us to understand the magnitude of technological and policy efforts that may be required to reduce fuel use of light-duty vehicle fleet.

A "future sales mix scenario" means the future sales share of new propulsion systems. In this research, Naturally-Aspirated Gasoline (Non-turbo Gasoline or Gasoline), Turbocharged Gasoline (turbo), Clean Diesel, Strong Gasoline Hybrid Electric Vehicle (HEV), Diesel Hybrid Electric Vehicle, Plug-in Hybrid Vehicle (PHEV), Battery Electric Vehicle (BEV), and Fuel Cell Vehicle (FCV) are taken into consideration as new propulsion systems in the future.

First of all, vehicles are divided into two types in order to build sales mix scenarios. The first type is called Standard Vehicles, which includes compact and normal passenger cars and compact trucks. The second type is called Light Vehicles, which includes K-cars and K-trucks. Then, four potential future sales mix scenarios were evaluated.

(1) Government Scenario

In June 2008, the then Prime Minister, Yasuo Fukuda, talked about the government's vision that "An ambitious target to introduce Next Gen Vehicles (new propulsion technology vehicles such as hybrid vehicles and battery electric vehicles) at the ratio of half of the total new car sales should be realized by 2020." Since the sales share of the new propulsion vehicles was only 11.8% in 2010, this government scenario might be too optimistic. The details of the Government Scenario are shown in Table 6, Figure 13, and 14 [MOE, 2010]. Since the Japanese Government has projected the number of sales of each new propulsion vehicle, the percentage is obtained based on the total sales projections in the future.

(2) Half of Government Scenario

The sales percentages of new technology (all propulsion systems except for conventional gasoline vehicles) in each year in this scenario are the halves of those in the Government Scenario. This scenario has been created because the Government Scenario is too optimistic and it is desirable to have a less optimistic scenario based on the Government Scenario objectives. The details of the Half of Government Scenario are shown in Table 7, Figure 13, and 14 [MOE, 2010].

(3) Realistic Scenario

This is an original scenario and has been developed, based on some expert opinions and our own forecast, to provide a separately developed more realistic alternative to the optimistic Government Scenario. The details of the Realistic Scenario are shown in Table 8, Figure 13, and 14.

(4) No-change Scenario

This scenario assumes that the sales mix, such as the sales share of hybrid vehicles or electric vehicles, does not change in the future.

Table 6. Sales mix of the Government Scenario
[MOE, 2010; NGVPC, 2010]

Gov't (standard)	Number of sales [thousands]			%		
	2010	2020	2030	2010	2020	2030
Gasoline				81.96%	34.08%	15.94%
Non-turbo (ICE)				*(81.96%)*	*(34.08%)*	*(15.94%)*
Turbo gasoline						
Diesel						
Clean diesel	4	186	134	0.13%	6.20%	4.66%
Gasoline hybrid				17.90%	37.48%	34.03%
Strong hybrid	*550*	*1067*	*924*	*(17.90%)*	*(35.58%)*	*(32.12%)*
Mild hybrid		*39*	*38*	*(0%)*	*(1.30%)*	*(1.32%)*
Micro hybrid		*18*	*17*	*(0%)*	*(0.60%)*	*(0.59%)*
Diesel hybrid		76	81	0%	2.53%	2.82%
Electricity						
PHEV	0.2	385	790	0.01%	12.84%	27.46%
BEV	0	201	360	0%	6.7%	12.51%
Hydrogen						
FCV	0	5	74	0%	0.17%	2.57%
Gov't (light)	Number of sales [thousands]			%		
	2010	2020	2030	2010	2020	2030
Gasoline				99.42%	74.98%	33.01%
Non-turbo (ICE)				*(84.50%)*	*(63.73%)*	*(28.06%)*
Turbo gasoline[2]				*(14.91%)*	*(11.25%)*	*(4.95%)*
Electricity						
BEV	10	474	1244	0.58%	25.02%	66.99%

2 Since 41 models of K-cars/trucks (light vehicles) out of a total of 238 models of light vehicles were turbo gasoline vehicles (17.2%) [Road Transport Bureau, MLIT, 2010], turbo gasoline-using light vehicles are assumed to be 15% of all the gasoline vehicles for light vehicles.

Table 7. Sales mix of the Half of Government Scenario

Half of Gov't (standard)	%		
	2010	2020	2030
Gasoline	82.10%	66.96%	58.00%
Non-turbo (ICE)	*(82.10%)*	*(66.96%)*	*(58.00%)*
Turbo gasoline			
Diesel			
Clean diesel	0%	3.10%	2.30%
Gasoline hybrid	17.90%	18.75%	17.00%
Strong hybrid			
Mild hybrid			
Micro hybrid			
Diesel hybrid	0%	1.30%	1.41%
Electricity			
PHEV	0%	6.40%	13.75%
BEV	0%	3.40%	6.25%
Hydrogen			
FCV	0%	0.09%	1.29%
Half of Gov't (light)	%		
	2010	2020	2030
Gasoline	99.42%	87.50%	66.50%
Non-turbo (ICE)	*(84.51%)*	*(74.38%)*	*(56.53%)*
Turbo gasoline	*(14.91%)*	*(13.13%)*	*(9.98%)*
Electricity			
BEV	0.58%	12.50%	33.50%

Table 8. Sales mix of the Realistic Scenario

Realistic (standard)	%		
	2010	2020	2030
Gasoline	82.1%	60.0%	35.0%
Non-turbo (ICE)	*(82.1%)*	*(57.0%)*	*(31.5%)*
Turbo gasoline		*(3.0%)*	*(3.5%)*
Diesel			
Clean diesel	0%	3.0%	5.0%
Gasoline hybrid	17.9%	20.0%	28.0%
Strong hybrid			
Mild hybrid			
Micro hybrid			
Diesel hybrid	0%	2.0%	2.0%
Electricity			
PHEV	0%	10.0%	20.0%
BEV	0%	5.0%	10.0%
Hydrogen			
FCV	0%	0.0%	0.0%
Realistic (light)	%		
	2010	2020	2030
Gasoline	99.42%	90.00%	75.00%
Non-turbo (ICE)	*(84.51%)*	*(76.5%)*	*(63.75%)*
Turbo gasoline	*(14.91%)*	*(13.5%)*	*(11.25%)*
Electricity			
BEV	0.58%	10.00%	25.00%

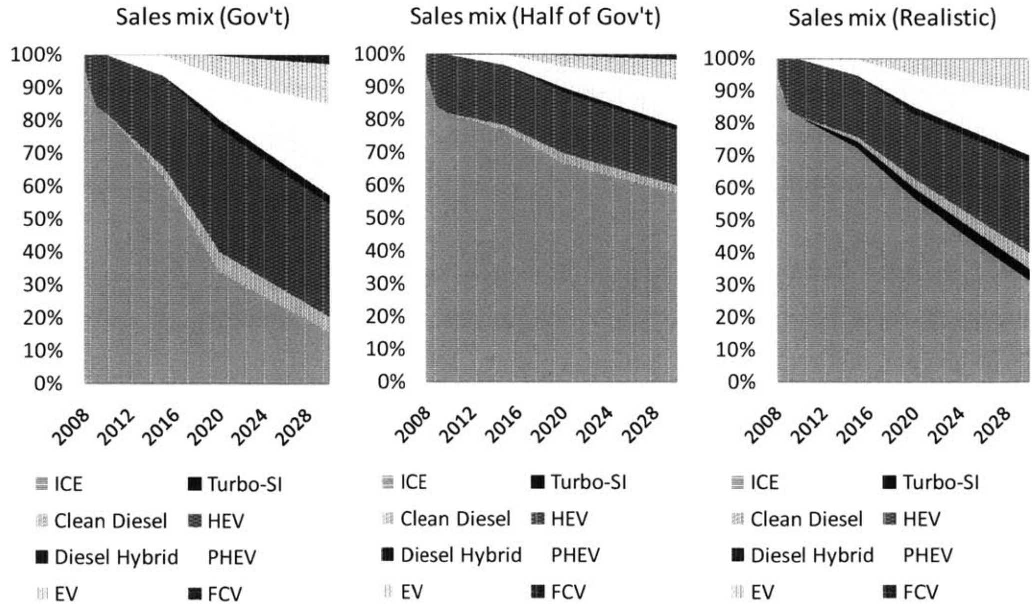


Figure 13. Sales mix scenarios for standard vehicles

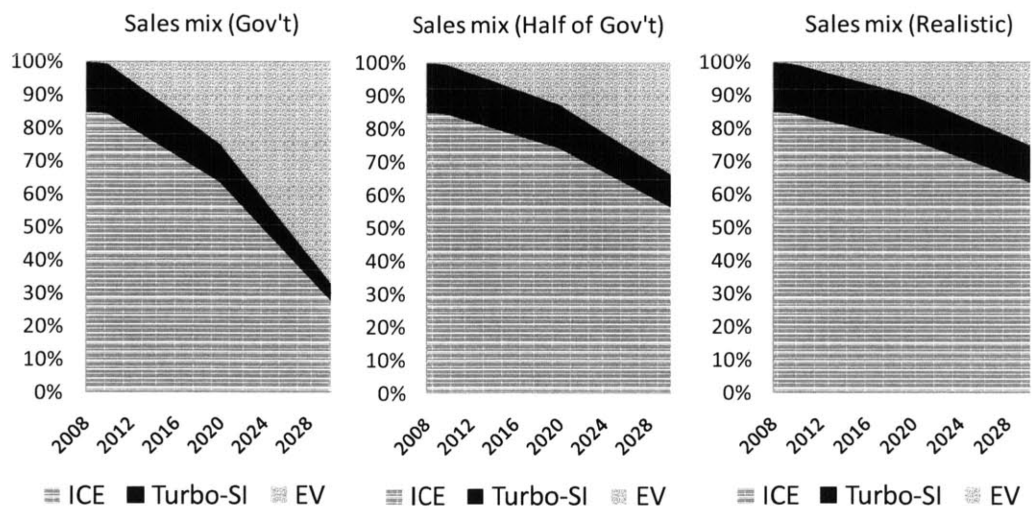


Figure 14. Sales mix scenarios for light vehicles

From Figure 13, the Half of Government Scenario assumes the most modest change for standard vehicles among these three scenarios. On the other hand, the Realistic Scenario assumes the most modest change for light vehicles among these three scenarios because some experts doubt that battery electric vehicles will become popular so soon.

2.2.6 Vehicle Weight

Though Vehicle Fuel Consumption is a necessary input for the Fleet Model, it is not available for all vehicle categories such as K-cars or compact trucks. Therefore, that information is obtained in the present research by using the relationship between fuel consumption and vehicle weight.

2.2.6.1 Average Vehicle Weight for each vehicle category

Since average vehicle weight sold in a certain year is not available, weight distributions of in-use vehicles in 2008 are shown in Figure 15 [AIRIA, 2010]. There is no official vehicle weight data for K-cars and K-trucks. According to the catalog data, however, most of the vehicle weights of K-cars and K-trucks sold in 2010 were in the range between 700kg and 1,070kg [Road Transport Bureau of MLIT, 2010].

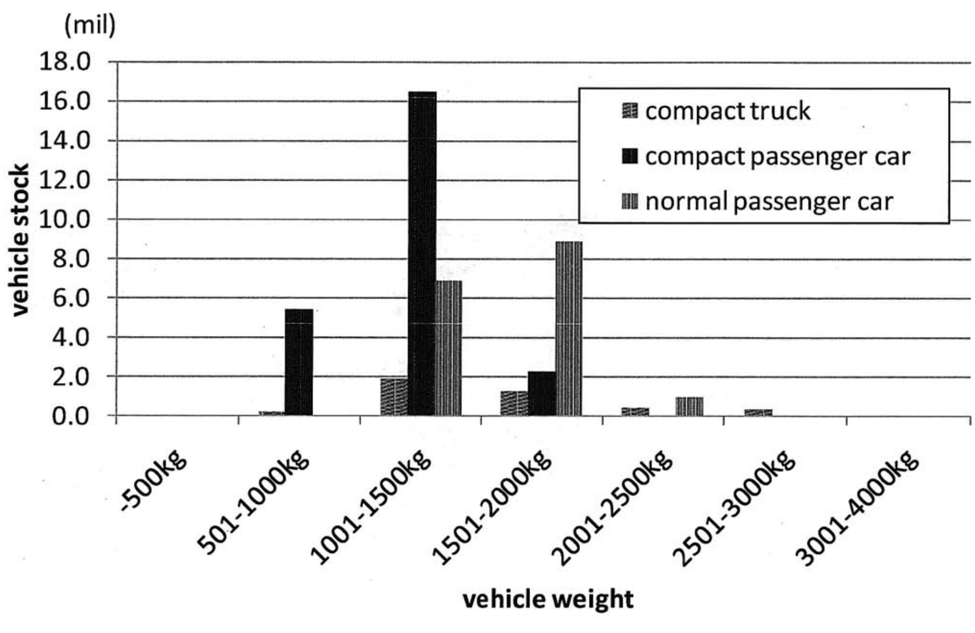


Figure 15. In-Use Vehicle Weight Distribution in Japan in 2008 [AIRIA, 2010]

The approximate average weight of vehicle in each category is shown in Table 9. As for compact passenger cars, normal passenger cars, and compact trucks, the average weights are obtained based on the in-use vehicle weight distribution, using the median of each range. As for K-cars and K-trucks, the average vehicle weights are obtained by considering catalog data.

Table 9. Average vehicle weight for each vehicle category

	Average Weight	Data Source
Compact truck	1625 [kg]	in-use vehicle weight distribution, 2008
Compact passenger car	1187 [kg]	in-use vehicle weight distribution, 2008
Normal passenger car	1573 [kg]	in-use vehicle weight distribution, 2008
K-car/ K-truck	850 [kg]	new vehicle catalog, 2010

2.2.6.2 Relationship between Fuel Consumption and Vehicle Weight

A precise relationship between vehicle weight and vehicle fuel consumption for light-duty vehicles in the United States has been identified [Cheah, 2010]. In the U.S. case, the adjusted, combined city/highway (55/45) fuel consumption and curb weight of all model year 2006-2008 light-duty vehicles offered in the U.S. revealed a general positive correlation.

Figure 16 plots the fuel consumption (L/100km) of new passenger vehicles (compact and normal passenger cars and K-cars) that were sold in 2008, measured by JC08 mode (Japanese test cycle) [Road Transport Bureau of MLIT, 2010]. There are 225 samples in the plots. As expected, a positive correlation was found for passenger cars sold in Japan. Based on the data, formulas for fuel consumption and vehicle weight (curb weight) were obtained as shown in Figure 16. The linear correlations, which are shown in Figure 16, are as follows:

(1): $y = 0.0066x - 0.6618$ (AT, MT)

(2): $y = 0.0047x + 0.6267$ (CVT)

(3): $y = 0.004x - 1.4279$ (HEV)

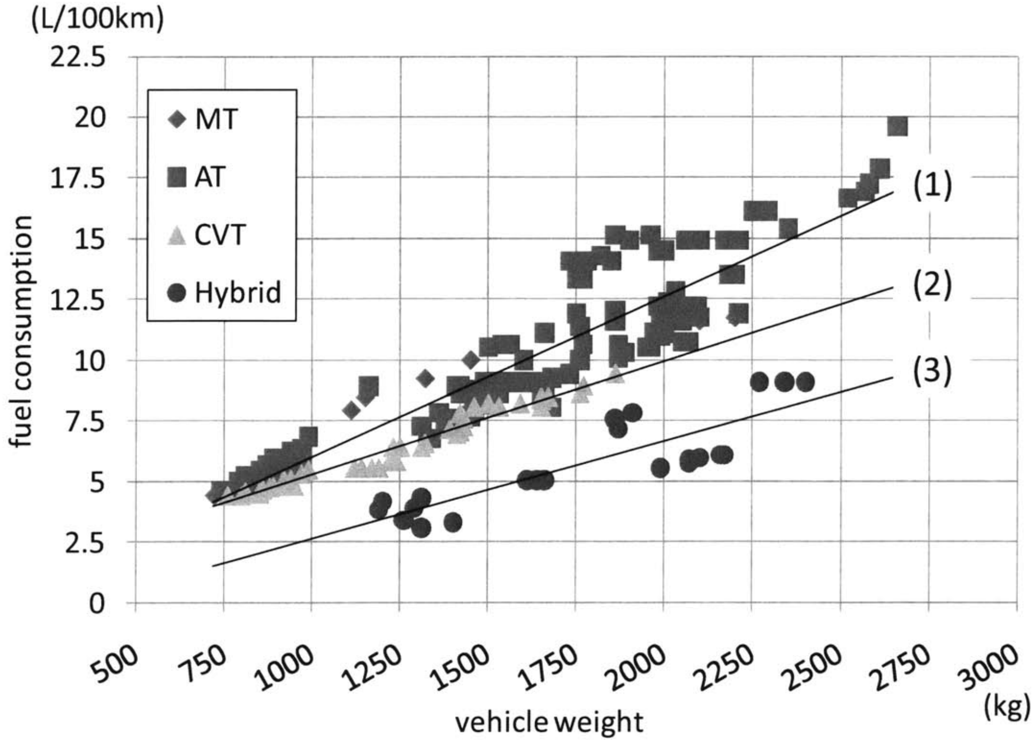


Figure 16. Fuel Consumption and Vehicle Weight by JC08 mode in Japan [Road Transport Bureau of MLIT, 2010]

Since most of the vehicles in Japan are AT (Automatic Transmission), the formula for AT and MT (Manual Transmission) is going to be used to calculate the fuel consumption by using the vehicle weight.

2.2.7 Vehicle Fuel Consumption

2.2.7.1 Historical Data of Vehicle Fuel Consumption for all passenger cars

It is very difficult to get consistent data for vehicle fuel consumption because there are two test cycles for measuring vehicle fuel economy. The first one is called the 10-15 mode cycle, which has been used for emission certification and fuel economy for light-duty vehicles. Emissions are expressed in g/km [JISHA, 1983]. The second one is called JC08 mode. This new JC08 chassis dynamometer test cycle for light vehicles (< 3,500kg GVW) was introduced when Japan's 2005 emission regulation was established. The test represents driving in congested city traffic, including idling periods and frequently alternating acceleration and deceleration [MLIT, 2006]. Measurement is made twice, with a cold start and with a warm start. The test is used for emission measurement and fuel economy determination, for gasoline and diesel vehicles. The

JC08 test will be fully phased in by October 2011. The driving schedules for both test cycles are shown in Figure 17 [MLIT, 2006]. The on-road fuel consumption is higher than the test values because of differences between actual driving conditions and trip patterns, and the test cycles, as well as the less than ideal state of maintenance of vehicles and aggressive driving behavior [Hellman and Murrell, 1982]. However, fuel consumption by test cycles is regarded as on-road fuel consumption in the present research.

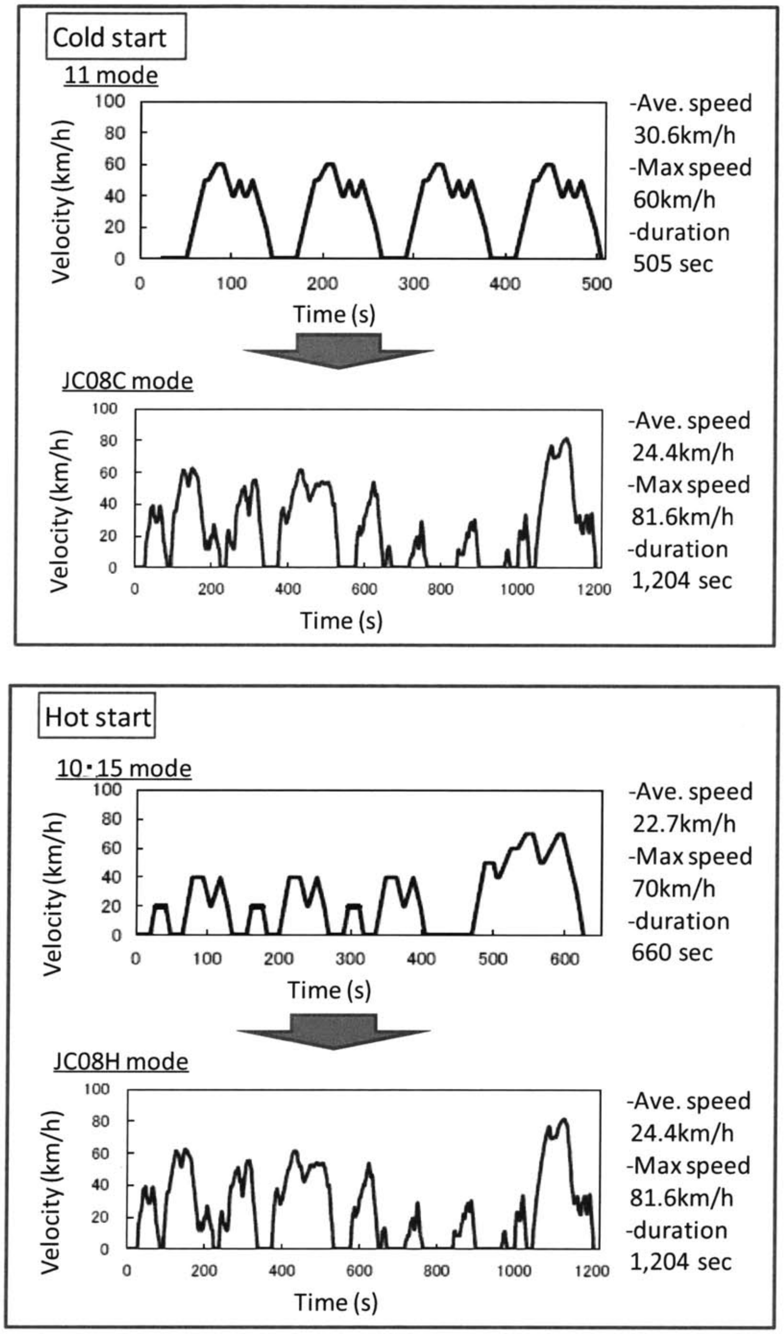


Figure 17. Japanese test cycles for measuring vehicle fuel economy [MLIT, 2006]

Figure 18 shows the new passenger car vehicle fuel consumption trend from 1993 to 2009 [Road Transport Bureau of MLIT, 2010; JAMA, 2010]. Vehicle fuel consumption in 2009 is obtained from JAMA's fuel consumption trend because the data has not yet become available from MLIT. Since the MLIT fuel consumption values are about 0.5[km/L] higher than JAMA reported fuel consumption values, the change of fuel consumption from 2008 to 2009 in JAMA's data was used in order to get tentative MLIT data for 2009. In addition, the historical data for fuel consumption is measured by 10-15 mode and converted to JC08 mode by the following formula [JSAE, 2007]:

$$\text{FC by JC08 [km/L]} = \text{FC by 10-15 [km/L]} * 0.913$$

Based on the Kyoto protocols, the Energy Conservation Law was revised in 1998 and it introduced Top-Runner Target Product Standards. The fuel economy targets were based on weight classes, and required 22.8% improvement over the 1995 weight class averages by the year 2010. The fuel economy target for passenger vehicles in 2015 is 16.8km/L (5.95L/100km), measured by JC08 mode. Since the fuel economy target is determined based on the vehicle weight range, this fuel economy is the average for passenger vehicles. Here, the vehicle weight distribution is assumed to be constant in the future.

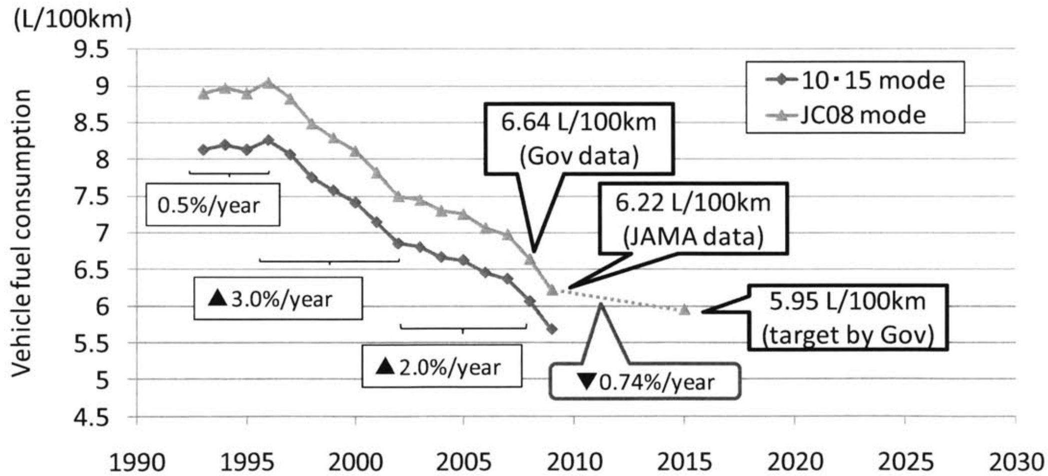


Figure 18. The trend of vehicle fuel consumption for all passenger vehicles [Road Transport Bureau of MLIT, 2010; JAMA, 2010]

2.2.7.2 Vehicle Fuel Consumption for each vehicle category of Model Year 2008

In Table 9, the average vehicle weight is obtained, though the source is different from one category to another. From this section, the average vehicle shown in Table 9 is regarded as vehicle weight sold in 2008 (Model Year 2008). From both Figure 16 (which shows the relationship between vehicle weight and fuel consumption) and Table 9 (which shows average vehicle weight for each vehicle category), vehicle fuel consumption for each vehicle category of Model Year 2008 is obtained, as shown in Table 10.

Table 10. Vehicle fuel consumption for each vehicle category of Model Year 2008

	Average Weight	Vehicle Fuel Consumption (JC08 mode)
Compact truck	1625 [kg]	10.06 [L/100km]
Compact passenger car	1187 [kg]	7.17 [L/100km]
Normal passenger car	1573 [kg]	9.72 [L/100km]
K-car/ K-truck	850 [kg]	4.95 [L/100km]

2.2.7.3 The trend of Vehicle Fuel Consumption for each vehicle category

In section 2.2.7.1, historical vehicle fuel consumption for all passenger cars, including compact and normal passenger cars, and K-cars, was obtained. From this data, the trends of how fuel economy has been improved can be seen. Based on the historical trends and vehicle fuel consumption in 2008, vehicle fuel consumption for each vehicle category is calculated and shown in Figure 19. Specifically, the historical percentage changes of fuel consumption for all passenger cars were used for the calculation.

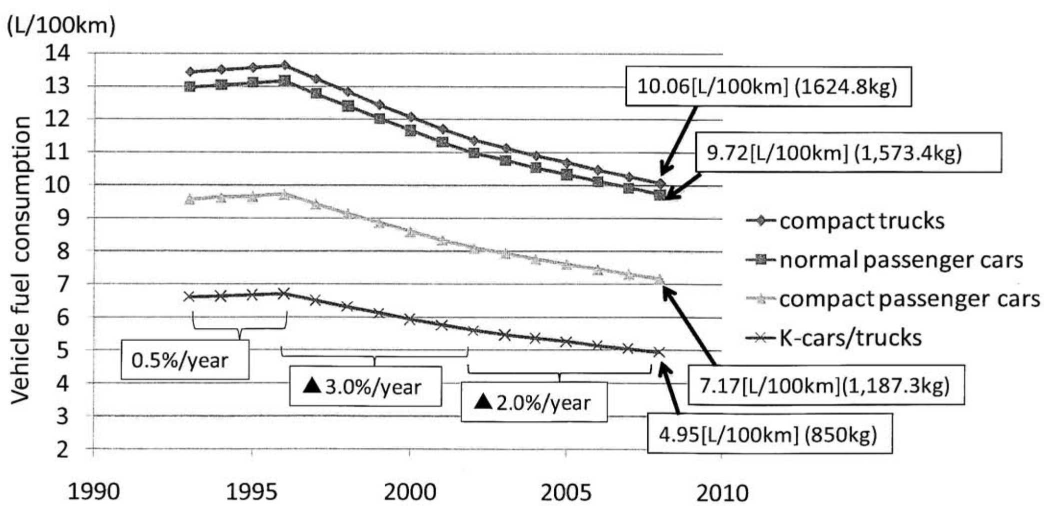


Figure 19. The trend of vehicle fuel consumption for each vehicle category

In the fleet model, fuel consumption is assumed to be constant before 1993 because no data is available. Although the trend of vehicle fuel consumption cannot be the same for all vehicle categories, especially because historical vehicle weight change is quite different from one vehicle category to another, the trends of vehicle fuel consumption for each vehicle category are assumed to be the same as that for all categories of passenger cars.

2.2.7.4 Future Reductions in Fuel Consumption

There are several technologies and approaches to improve vehicle fuel consumption. They include improvements in the engine and transmission and use of alternative propulsion systems such as hybrid vehicles. In this section, the following two approaches are explained.

<Vehicle performance and size trade-off>

The fuel consumption trend that is realized in practice will depend on the degree of emphasis placed on reducing fuel consumption, because fuel consumption reductions can be offset by the negative impacts of increasing vehicle size, weight, and power. For the purpose of understanding the influence of the trade-off of the performance, size, and fuel consumption, the concept of Emphasis on Reducing Fuel Consumption (ERFC), which is shown in Equation 2, is helpful. [Heywood, 2010]

$$\mathrm{ERFC} = \frac{\text{Fuel Consumption (FC) Reduction Realized on Road}}{\text{FC Reduction Possible with Constant Performance and Size}} \quad (2)$$

ERFC measures the degree to which improvements in technology are being directed toward reducing onboard fuel consumption.

<Alternative propulsion systems>

Since fuel consumption reduction is realized not only by the improvement of mainstream gasoline vehicles, but also by the prevalence of new propulsion systems such as hybrid vehicles and battery electric vehicles, it is necessary to consider future reductions in vehicle fuel consumption for different propulsion systems. The relative fuel consumptions of different propulsion systems are shown in Figure 20 [MOE, 2010]. In the years between 2010 and 2020, or 2020 and 2030, the relative fuel consumption is assumed to change linearly. Technical progress in internal combustion engines has historically been roughly linear and relatively well-behaved [Chon and Heywood, 2000;

Heywood and Welling, 2009], which supports the linear assumption going forward.

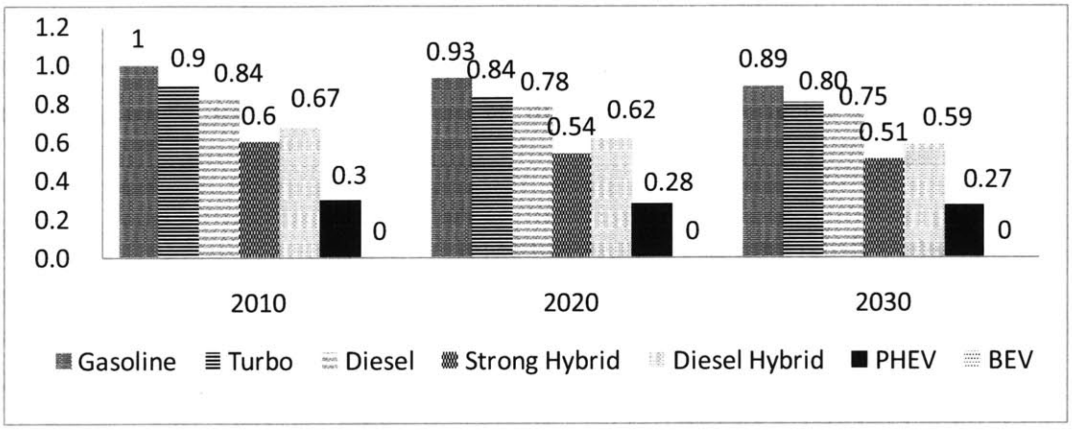


Figure 20. Relative fuel consumption for different propulsion systems [MOE, 2010]

These Japanese Government fuel consumption numbers for 2030 correspond to numbers for 2030 calculated for the U.S. or EU when the ERFC is about 50%. Comparing the relative fuel consumption of US/EU and Japan, there are two major differences.

(1) The mainstream gasoline engine of Japan does not improve as much as that of the US and EU.

This is because vehicle fuel consumption in Japan is already lower than that in the US and EU. Therefore, the potential reduction in fuel consumption is not so large in Japan.

(2) The relative fuel consumption for strong gasoline hybrid is smaller than that for diesel hybrid in Japan, though it is the opposite in the US and EU.

Strong Hybrid is most effective in the following conditions: 1) repeated acceleration and running at a low speed, and 2) light vehicle weight. Since both the JC08 test cycle, which represents driving in congested city traffic, and Japanese small vehicle size suit these conditions, a strong hybrid system can achieve lower fuel consumption in Japan successfully.

2.3 Model Calibration

Before the fleet model is used to simulate future fuel use and GHG emissions, it must first be calibrated using historical data. This will help ensure that the characteristics of the current fleet contained in the model correspond closely to the actual on-road fleet in Japan. The model calibration can be seen in the following chapter.

3. NEARER-TERM FLEET FUEL USE AND GHG TRENDS (through 2030)

3.1 Vehicle Stock

Before comparing future projections of light-duty fleet characteristics, the model results are first evaluated against historical trends. Figure 21 shows the model calculated vehicle stock compared with data by the Automobile Inspection and Registration Information Association [AIRIA, 2010]. The number of vehicles in the Japanese light-duty vehicle fleet increased from about 65.3 million vehicles in 1997 to about 71.4 million vehicles in 2006. Then, it decreased to 71.0 million vehicles in 2009. The increase in stock came from the light vehicles, especially K-cars. However, the total numbers in the light-duty vehicle fleet started slightly decreasing from 2007 because the number of standard vehicles has been decreasing rapidly. In Figure 21, the model results are very close to the historical fleet data. Detailed data for each vehicle category is shown in Figure 22.

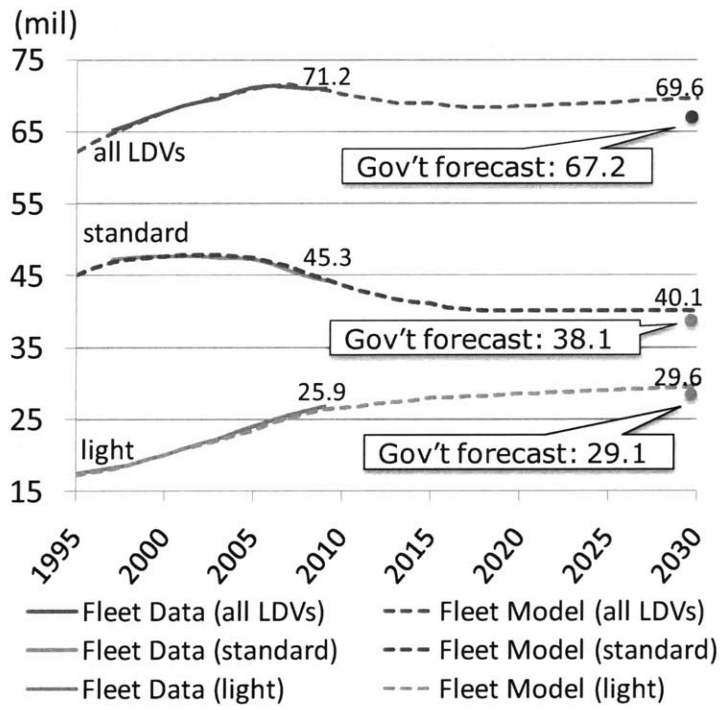


Figure 21. Vehicle stock (fleet model results compared with historical data) [AIRIA, 2010; MOE, 2010]

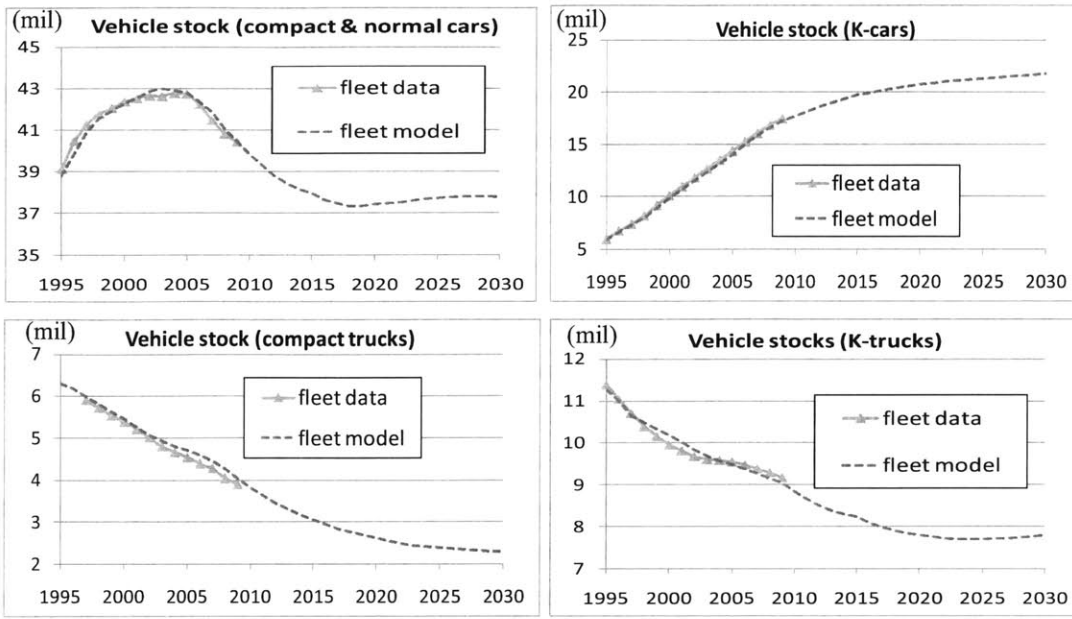


Figure 22. Vehicle stock for each vehicle category
(Fleet model results compared with historical data)
[AIRIA, 2010]

Table 11 shows the average error in the light-duty vehicle stock since 1997 relative to the AIRIA data. The error between data and model is less than 0.3% in any time period, which means this fleet model forecasts the number of light-duty vehicles correctly if the future assumptions of inputs are correct.

Table 11. Difference between fleet data and model calculation

Period	Difference in light-duty vehicle stock [%]
1997-2000	0.30%
2001-2005	-0.02%
2006-2009	-0.04%

There are several reasons for the decrease or increase of vehicle stock of each category.

<Compact and normal passenger cars>

The reasons for the decrease of the compact and normal passenger car stock from 2005 are as follows:

1. Recession and high gasoline price.

2. The number of people who purchase passenger cars for the first time has been decreasing because passenger cars have long been widely owned in Japan. In other words, when new cars are sold, old cars are scrapped, in most cases.
3. The increase of driver's license holders (80 million in 2009) has been much slower. This is because of the decreasing population, in particular the decrease of the population of younger generations.

<K- cars>

In contrast to the compact and normal passenger cars, the K-car stock has still been increasing because the new K-car sales have not dropped rapidly yet. The reasons for the increase of new K- car stock from 2005 are as follows:

1. Due to the high gasoline price, some drivers prefer K-cars to compact and normal cars. Drivers can save money on gasoline because fuel economy for K-cars is better than that for compact and normal passenger cars.
2. Taxes for K-cars, such as vehicle weight tax, vehicle tax, and vehicle acquisition tax, are lower than those for compact and normal passenger cars. Details on taxes are shown in Table 12 [Road Transport Bureau, MLIT, 2011; NAVI, 2011; TMG, 2008].

However, the global recession slowed the increase of the K-car stock.

Table 12. Taxes for passenger cars in Japan
[Road Transport Bureau, MLIT, 2011; NAVI, 2011; TMG, 2008]

	Payment time	K-cars	Compact & normal passenger cars
Vehicle acquisition tax	when purchased	3% of the car price	5% of the car price
Vehicle weight tax	every 2 years	JPY 7,600	JPY 10,000~60,000 (Depending on vehicle weight)
Vehicle tax	every year	JPY 7,200	JPY 29,500~111,000 (Depending on displacement)

<Compact trucks>

The reasons for the decrease of compact truck stock are as follows:

1. Recession and high gasoline price
2. In the Japanese logistic system, more efficient freight transport has been achieved. Logistic companies have gradually come to choose larger trucks rather

than smaller trucks from the perspective of both cost and environmental burden. In addition to this, a modal shift from trucks to ships or rail is highly promoted in Japan. As a result, the number of compact trucks has been decreasing and will decrease in the near future.

<K- trucks>

The reasons for the decrease of K-truck stock are the same as those for compact trucks. The decreasing rate of stock in K-trucks is smaller than that of stock in compact trucks. This is probably because of the tax. Since taxes for K-trucks are lower than those for compact trucks, truck users have an incentive to change from compact trucks to K-trucks.

From the near future through 2035, the vehicle stock of standard vehicles is going to decrease for a few years and level off. The reason for leveling off in spite of the decrease of sales is that the average lifetime is getting longer. In contrast, the vehicle stock of light vehicles is going to increase and level off. The forecast of vehicle stock by the government is shown in Figure 21. The government forecast of vehicle stock for all light-duty vehicles is smaller than the fleet model calculation by 3.4%. This is because the growth of average lifetime is assumed to be very small in the government's forecast, which is not consistent with the historical data of the rapid growth of average lifetime.

3.2 Fleet VKT

The Vehicle Kilometers Traveled calculated by the Fleet Model is shown in Figure 23. Since there is no data available for the light-duty vehicle fleet VKT, the model data is compared with two kinds of data from 2008 by the government [Information Security, Research and Statistics Division of MLIT, 2010]. The first kind (data A) is that of all LDVs and normal trucks, and the second (data B) is that of all LDVs without compact trucks. The scope of data is shown in Table 13. The model data appear between data A and data B, which shows that the error between the model and data must be rather small. The model result is closer to data B than data A. The first possible reason is that the fleet VKT of normal trucks is so large that data A shows a large number. The second possible reason is that the VKT per vehicle is assumed to decrease at such a high annual rate that the fleet VKT is estimated to be too small. The annual decrease rates of 6.5% (for passenger cars) and that of 6.2% (for trucks) were assumed to be constant in each model year in the present research. However, as average lifetimes of vehicles get longer, the annual decrease rate should be getting smaller.

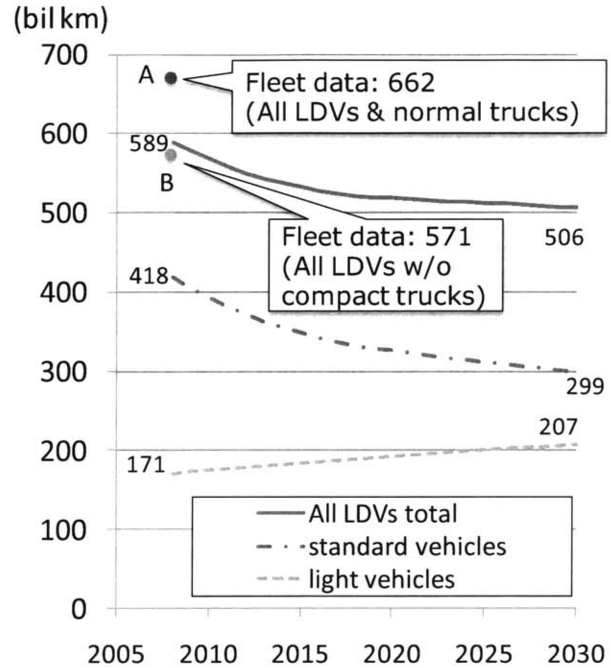


Figure 23. Total fleet VKT in the future
[Transport Research and Statistics Office, MLIT, 2010]

Table 13. The scope of data and fleet model

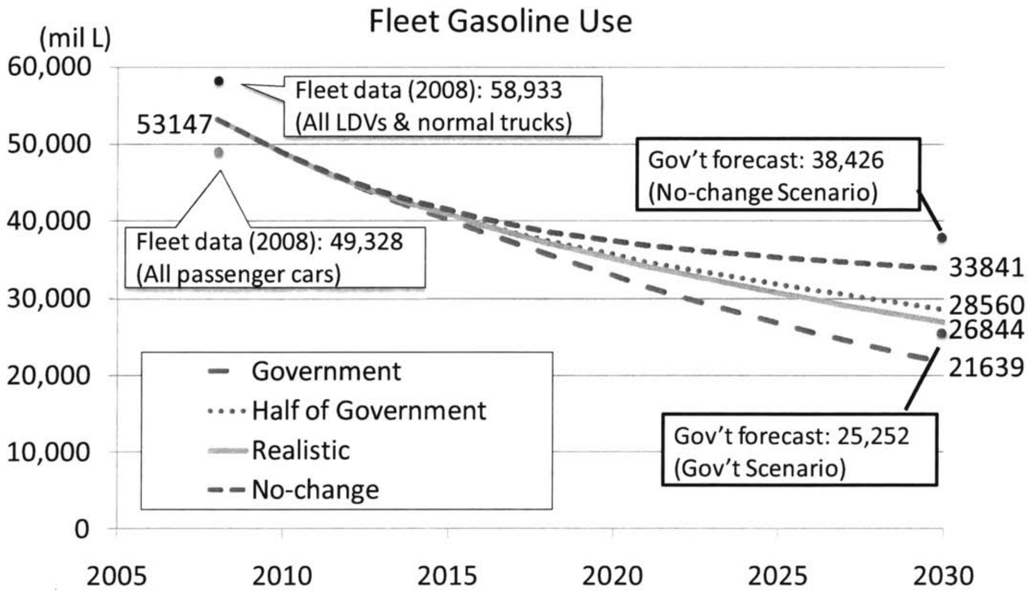
	scope			
Data A	All passenger cars	K-trucks	Compact trucks	Normal trucks
Fleet model	All passenger cars	K-trucks	Compact trucks	Normal trucks
Data B	All passenger cars	K-trucks	Compact trucks	Normal trucks

The total VKT for all light-duty vehicles is forecast to decrease by 14% from 2008 to 2030. This trend results from a decrease in the number of vehicles in use and a decrease in VKT per vehicle for standard vehicles. The fleet VKT for standard vehicles in 2030 is projected to be two-thirds of that in 2008. In contrast, the fleet VKT for light vehicles is forecast to increase by 21% in 2030 compared with the level in 2008.

3.3 Fleet Fuel Use

The fuel use of the entire fleet is calculated by summing up the fuel use of vehicles using different technologies of the same age, which in turn is calculated by multiplying the number of vehicles in service of that age and technology type by the number of vehicle kilometers traveled, and then by their respective fuel consumption. Fuel use is calculated separately for each propulsion system type in gasoline equivalent units.

The results of the fleet fuel use from all light-duty vehicles in Japan are shown in Figure 24. As Figure 24 shows, the fleet gasoline use is projected to decrease in the future in every scenario. In the Government Scenario, the fleet gasoline use in 2030 is 59% less than in 2008. Even in the No-change Scenario, the fleet gasoline use in 2030 is 36% less than in 2008. To be clear, the No-change Scenario means "no sales mix change," and this scenario considers the improvement of fuel economy in the future as explained in section 2.2.7.4 (Future Reductions in Fuel Consumption). The reason for this decreasing trend of fuel use even in the No-change Scenario is the fleet VKT decrease in standard vehicles, which is derived from both the decrease in the vehicle stock and the decrease of VKT per vehicle. As for diesel use, the increase trend comes from the expected sales increase of clean diesel vehicles. The reason why the diesel use was assumed to be zero in 2010 is that conventional diesel vehicles are not taken into consideration in the present research. Conventional diesel vehicles are left out because the share of diesel vehicles of all passenger cars was only 0.1% in 2002 and has remained extremely low since then [METI, 2005].



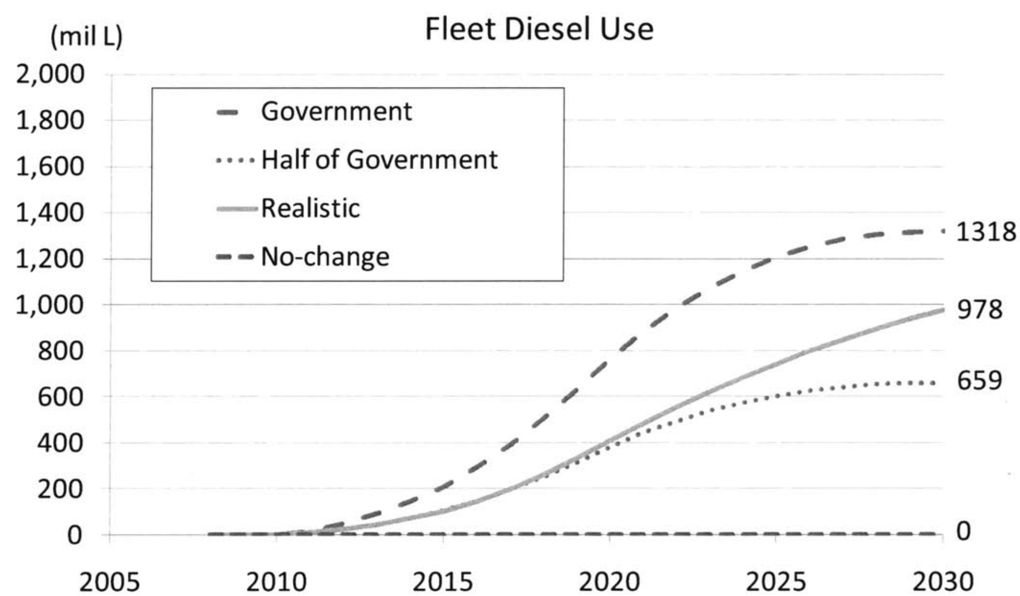


Figure 24. Fleet fuel use
[MLIT, 2010; MOE, 2010]

The forecasts of gasoline use by the fleet model are compared with the fleet data in 2008 and the government's calculation in 2030. As for the comparison in 2008, the fleet model calculation is low, taking into consideration the fact that most of the normal trucks use not gasoline but diesel. This is because the fuel economy on roads is not as good as that measured by JC08 mode. As for the calculations of the gasoline use in 2030, there are two kinds of forecasts by the government. The first one is calculated by assuming that new propulsion systems such as hybrid vehicles will become popular by then (Government Scenario). The second one is calculated by assuming that the sales mix is constant from now on and that only the improvement of fuel economy is considered (No-change Scenario). The gasoline use calculated by the fleet model is estimated to be lower than that by the government by 16% in the Government Scenario and by 12% in the No-change Scenario. Even though the gasoline use is already estimated to be lower in 2008 by the fleet model, the difference in each scenario between the government calculation and the fleet model calculation is not small. This is probably because of the difference in VKT forecasts. In the present research, VKT per vehicle per year is assumed to decrease as vehicles become older. However, the government does not seem to have taken this into consideration. Unfortunately, the way that VKT per vehicle per year is treated by the vehicle age in the government calculation is unclear, and even comparison of fleet VKT is impossible because of the lack of government calculation data of VKT. The cumulative VKT data in 2009 showed that VKT per vehicle per year decreases as vehicles become older. Therefore, the result from the fleet model should reflect actual vehicle usage more than the result from government calculations.

Figure 25 shows the fleet fuel use by standard vehicles and light vehicles in each scenario. The large reduction of gasoline use comes from the decrease of gasoline use by standard vehicles. In the Government Scenario, the fleet gasoline use by standard vehicles in 2030 is about one-third of that in 2008, and the gasoline use by light vehicles in 2030 is about two-thirds of that in 2008. In the No-change Scenario, in spite of the increased vehicle stock and VKT per vehicle, the gasoline use by light vehicles in 2030 is about 95% of that in 2008. This result is because of the improvement of fuel economy of mainstream gasoline vehicles. As for the Half of Government and Realistic Scenarios, the trends of total gasoline use are similar. The total gasoline use in 2030 would be only about half of that in 2008 in both scenarios.

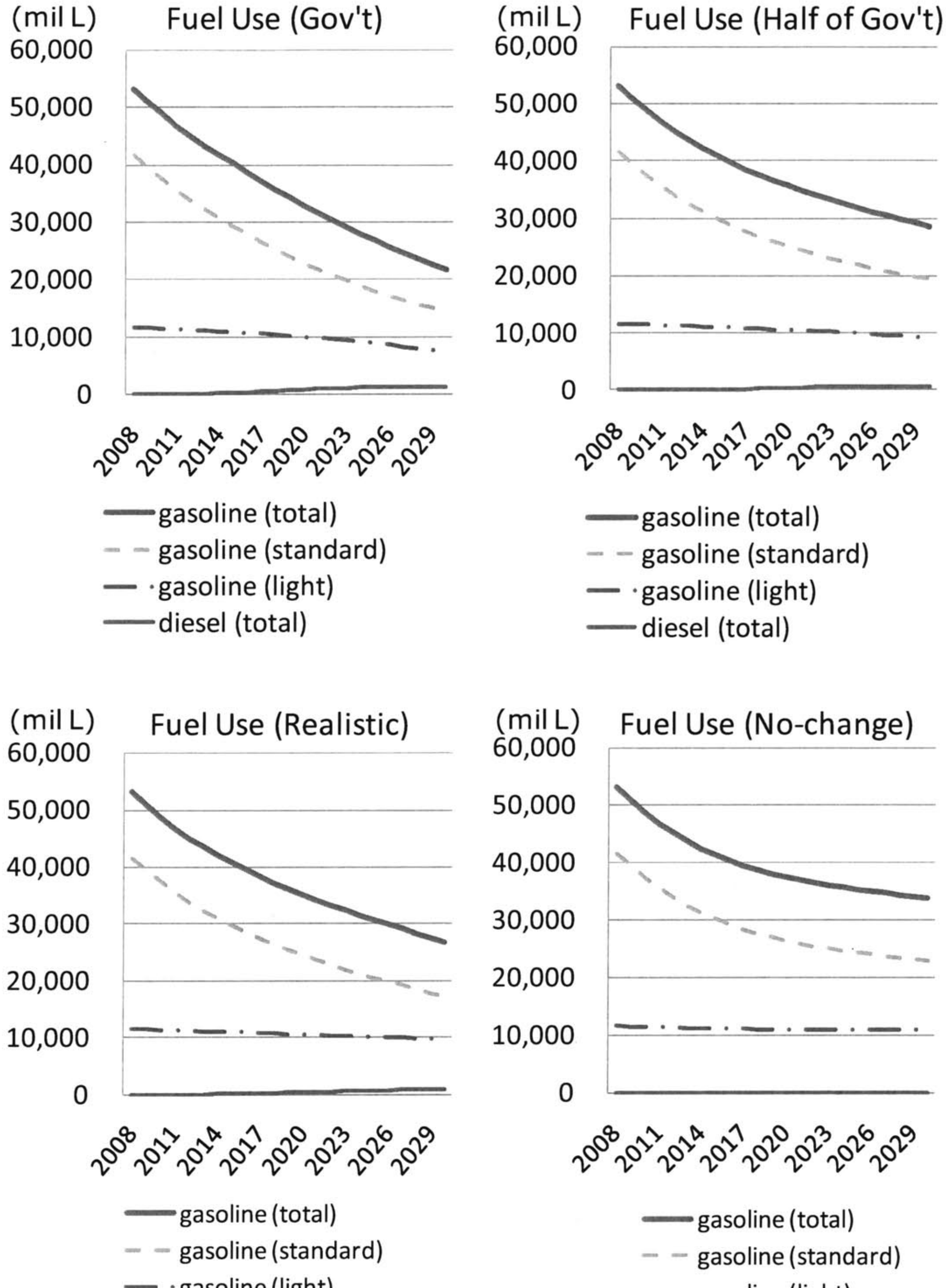


Figure 25. Fleet fuel use for each scenario

3.4 Fleet Electricity Use

The result of the fleet electricity use from all light-duty vehicles in Japan is shown in Figure 26. In the Government Scenario, the fleet electricity use increases because of the large sales share of battery electric vehicles and plug-in hybrid vehicles. Since 1,000 GWh of electricity is equivalent to 104 million liters of gasoline in chemical energy[3], 17,584 GWh of electricity is equivalent to about 2,000 million liters of gasoline in chemical energy. Though the life-cycle emissions factors are not considered and the chemical energy equivalence cannot be used for the GHG emission comparisons, this conversion to chemical energy may help in understanding the scale of electricity use compared with the fuel use.

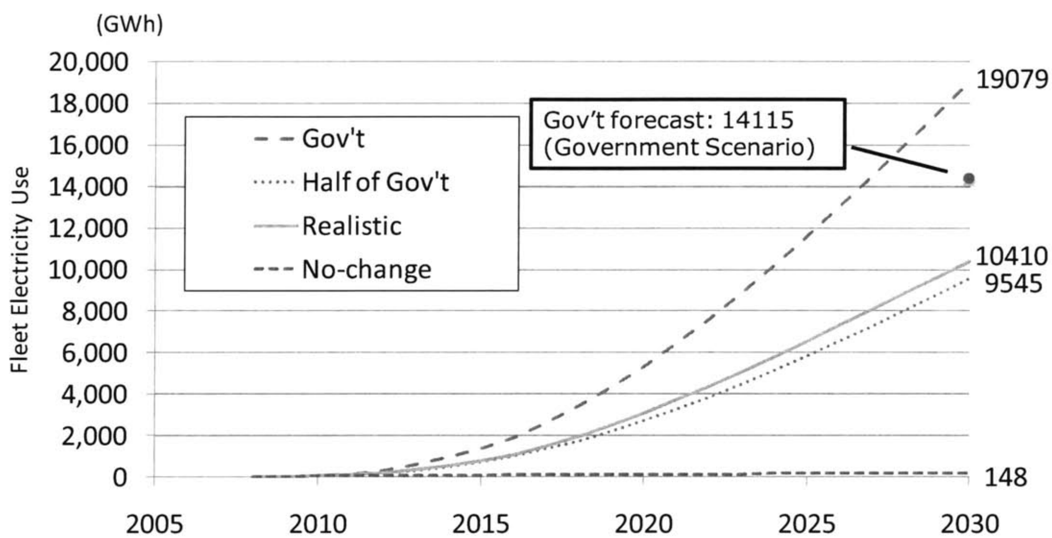


Figure 26. Fleet electricity use
[MOE, 2010]

In Figure 26, the forecast of electricity use by the fleet model is compared with the government's calculation for 2030, which is about 25% lower than the result from the fleet model. The discrepancy comes from the different assumptions about electricity consumption in the future. In the government's calculation, the efficiency of vehicles under electric operation is projected to increase just as fuel economy is going to

[3] Gasoline: 1[L] = 34.6 [MJ], Electricity: 1[kWh] = 3.6 [MJ],
Therefore, 1,000 [GWh] (electricity) = $3.6*10^9$ [MJ],
which is equivalent to $3.6*10^9$ [MJ] / 34.6 [MJ] = 104.0 [mil L] (gasoline).

improve, because electricity consumption is modeled based on gasoline consumption. However, in the present research, electricity consumption is set to be 0.15 [kWh/km] for standard vehicles [IEA, 2009] and 0.124 [kWh/km] for light vehicles [Nissan, 2010] and is kept constant in the future. There are three reasons for this. First, in contrast to fuel consumption, it is not yet clear how soon and to what extent battery efficiency is going to improve. Second, though fuel economy targets have been big incentives for improving fuel consumption, there is and will be no target to economize on electricity consumption in the near future. Third, it is not clear whether battery electric vehicles are going to become simpler or more complicated over time. For example, if the vehicle demands or requirements for interior systems such as heating and cooling increased, or if electronic functions became more complicated, electricity consumption would rise. On the other hand, technology may improve electricity use efficiency. Therefore, electricity consumption is projected to be constant in the present research.

Figure 27 shows the fleet electricity use from standard vehicles and light vehicles in each scenario. Since fleet electricity use differs widely depending on the scenario, the scale of the vertical axis for the No-change Scenario is different in each scenario. Though the trends of total fleet electricity use are similar in the Half of Government and Realistic Scenarios, the characteristics are not similar at all. In the Half of Government Scenario, electricity use from standard vehicles is about three-fourths of that from light vehicles. On the other hand, in the Realistic Scenario, electricity use from standard vehicles is one-and-a-half times as much as that from light vehicles. This is because the Realistic Scenario does not project a high sales share of battery electric vehicles in light vehicles. In the No-change Scenario, fleet electricity use is very small but is increasing, because the sales share of battery electric vehicles in the light vehicles was 0.58% in 2010 and will continue to be 0.58% through 2035. Since electricity use from standard vehicles is close to zero in the No-change Scenario, the line for fuel electricity from light vehicles overlaps with that for total fleet fuel electricity use in Figure 27.

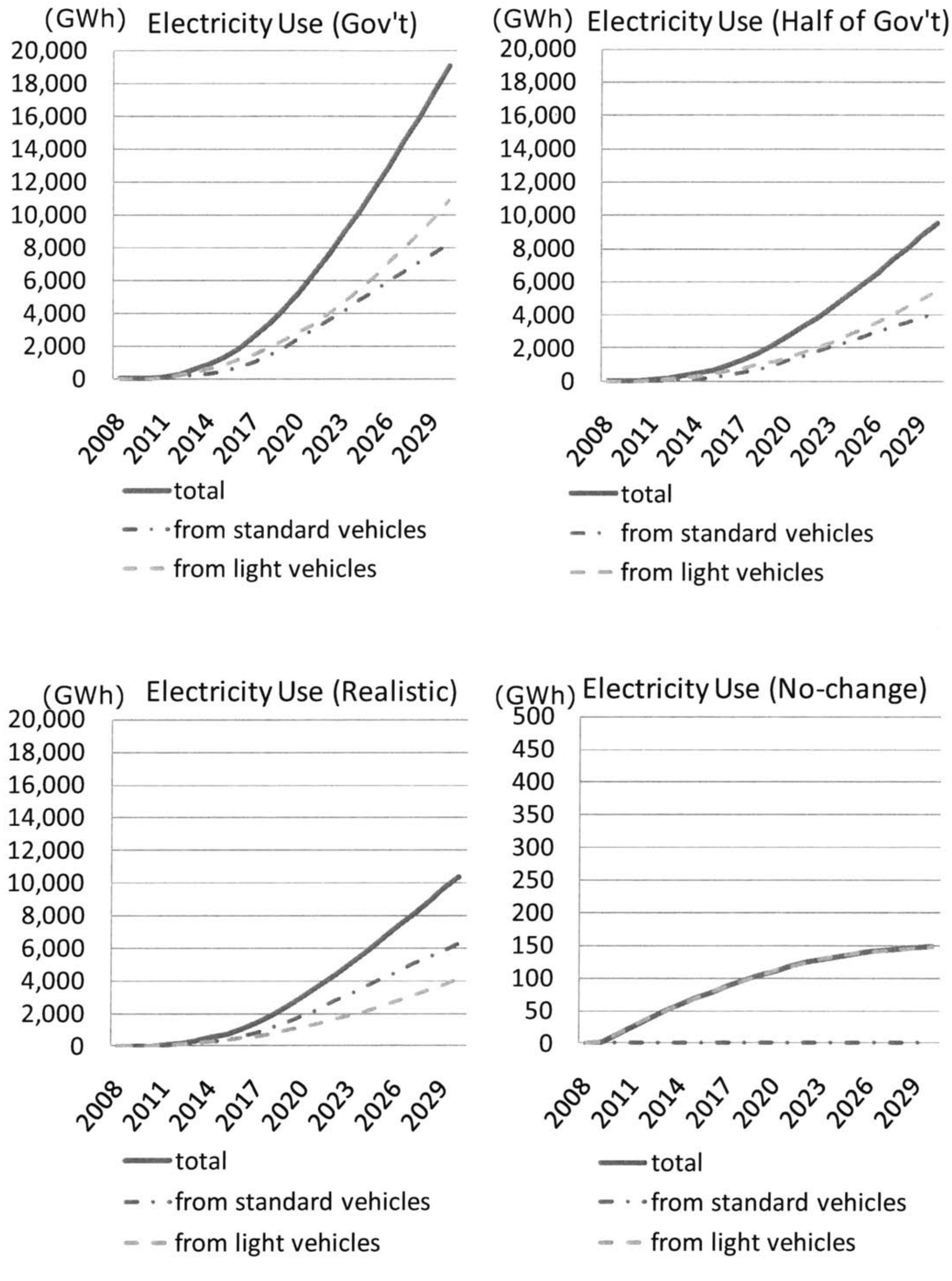


Figure 27. Fleet electricity use for each scenario

3.5 Fleet GHG Emissions

Greenhouse gas emissions are calculated on a well-to-wheel basis by multiplying the fuel use by a corresponding well-to-tank and tank-to-wheel greenhouse gas emissions coefficient. The life-cycle emissions factors used to calculate future vehicle fleet GHG emissions are shown in Table 14 [MOE and METI, 2010; JHFC and JARI, 2006; IEA, 2009].

Table 14. Energy use and CO2 emission factors
[MOE and METI, 2010; JHFC and JARI, 2006; IEA, 2009]

	Energy use	GHG Emissions		
		Fuel Cycle (Well to Tank) [g-CO2/MJ]	Vehicle operation (Tank to Wheel) [g-CO2/MJ]	Total (Well to Wheel) [g-CO2/MJ]
Gasoline	34.6 [MJ/L]	16.1 (JHFC)	67.1 (Gov's guideline)	83.2
Diesel	38.2 [MJ/L]	8.6 (JHFC)	68.6 (Gov's guideline)	77.2
Electricity (Average JPN mix)	3.6 [MJ/kWh]	122 (JHFC) 125 (IEA, data of 2007)	0	122 (JHFC) **125** (IEA, data of 2007)
Hydrogen	142 [MJ/kg]	74.9 ~136 (JHFC)	0	74.9~136 **105** (median for model)

All emission factors are calculated on a lower heating value (LHV) basis. More details about electricity and hydrogen are explained below.

<Electricity>

The use of electricity in light-duty vehicles will grow as plug-in hybrid vehicles and battery electric vehicles enter the market in large numbers. While this may help to displace petroleum use, the GHG emissions reductions will depend on the efficiency of vehicles under electric operation, and the GHG intensity of the electricity [Bandivadekar et al., 2008]. For example, GHG emissions from coal are 318.6 [g-CO2/MJ], and those from natural gas are 161.9 [g-CO2/MJ] [Bandivadekar et al., 2008]). Therefore, the grid mix is important in estimating the GHG emissions derived from electricity use. Electricity generation by source in Japan and the U.S. is shown in Figure 28 [IEA, 2009]. Based on this electricity generation in Japan, the GHG emissions from the Japan electricity grid are 125 [g-CO2/MJ][4] [IEA, 2009]. In the present research, the GHG emissions from the Japan electricity grid are projected to be constant in the future because of the following two reasons. First, the GHG emissions from the Japan electricity grid (125 [g-CO2/MJ]) are already much lower than those from the U.S. grid (213.6 [g-CO2/MJ] [Bandivadekar et al., 2008]), mainly because the share of coal in the Japan electricity grid mix is smaller than that in the U.S. Therefore, the reduction of the GHG emissions from Japan's electricity grid is more difficult to achieve than that from the U.S. Second, the Japan grid mix will not be likely to become more dependent on nuclear, which produces a smaller amount of GHG emissions than other sources of electricity generation, due to the huge earthquake that occurred in the northeastern part of Japan on March 11, 2011.

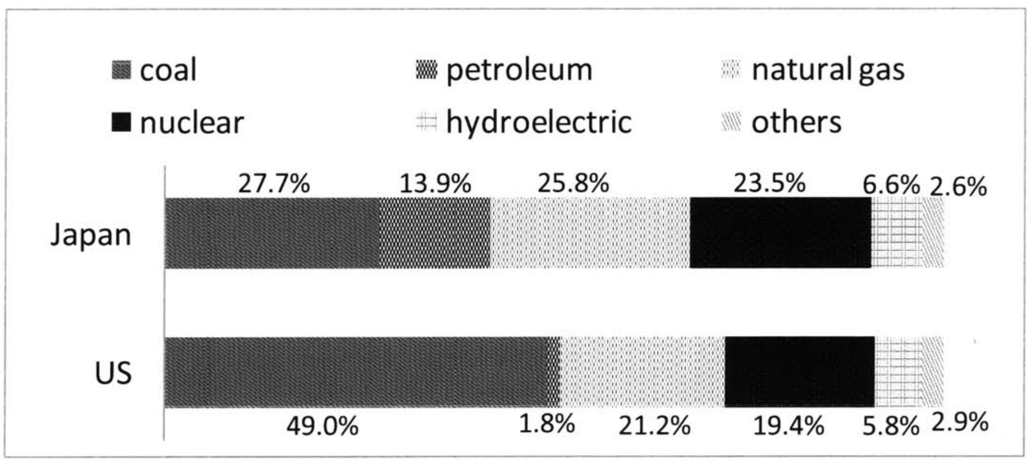


Figure 28. Electricity generation by source
[IEA, 2009]

The tank-to-wheel emissions for electricity are zero, as electricity does not consume any hydrocarbons during the vehicle operation phase.

<Hydrogen>

Like electricity, hydrogen can be produced from a variety of fuel sources. In Japan, industrial hydrogen is produced from sulfur-free gasoline, naphtha, methanol, kerosene, liquefied petroleum gas, and compressed natural gas. In addition, during the initial

---

4 CO2 emissions per kWh from electricity and heat generation were 450[g-CO2/kWh] in 2007. Since 1[kWh] = 3.6[MJ/kWh], the GHG emissions from Japan electricity grid are 450/3.6 = 125 [g-CO2/MJ]

phase of hydrogen fuel cell vehicles, the demand for hydrogen will be small and hydrogen is likely to be produced at distributed locations, even though centralized production of hydrogen will produce less GHG emissions. Since there were twelve hydrogen stations in 2004, well-to-tank GHG emissions for hydrogen production were calculated based on the characteristics of these stations [JHFC and JARI, 2006].
The tank-to-wheel emissions for hydrogen are zero, as hydrogen does not consume any hydrocarbons during the vehicle operation phase.

Figure 29 shows the result for the fleet GHG emissions. The upper four lines are fleet GHG emissions from total light-duty vehicles (both standard and light vehicles.) The middle four lines are fleet GHG emissions from standard vehicles. The lower four lines are fleet GHG emissions from light vehicles.

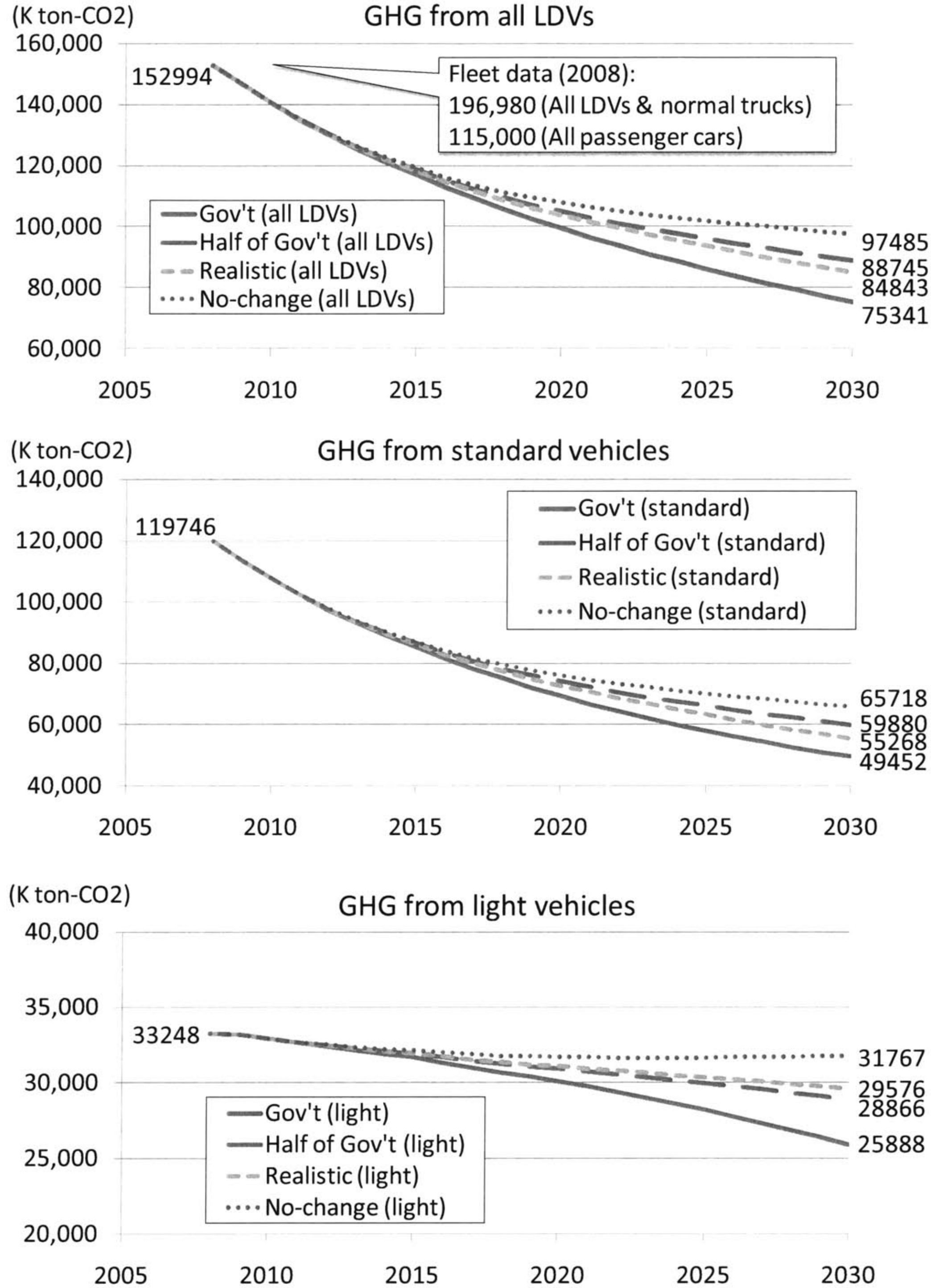


Figure 29. Fleet GHG emissions

[MOE et al., 2010]

In the Government Scenario, the total fleet GHG emissions in 2030 are less than half of those in 2008. Even in the No-change Scenario, the total fleet GHG emissions in 2030 are less than two-thirds of those in 2008. These big reductions are due to the decrease of fleet GHG emissions from standard vehicles. In the Government Scenario, the fleet GHG emissions from standard vehicles in 2030 are about 60% down from those in 2008. In the No-change Scenario, the fleet GHG emissions from standard vehicles in 2030 are 55% of those in 2008.

As for light vehicles, the fleet GHG emissions in 2030 are 22% down from those in 2008 in the Government Scenario, and 4% less in the No-change Scenario. The fleet GHG emissions reduction from light vehicles is quite small because of the increasing vehicle stock and fleet VKT.

Overall, the trends of fleet GHG emissions are similar to those of fleet gasoline use because fleet electricity use has less impact on GHG emissions compared with fleet gasoline use.

According to the government's calculation, the difference of the amount of GHG emissions between the Government Scenario and the No-change Scenario in 2030 will be 26,332 [k ton CO2], which is achieved by the decrease of gasoline use and the increase of electricity use [MOE, 2010]. In this research, the difference of the amount of GHG emissions between the Government Scenario and the No-change Scenario in 2030 will be 22,144 [k ton CO2]. There are three possible reasons for the difference between the government calculation and the fleet model calculation. First, the scope of the calculation is slightly different. In the government results, all light-duty vehicles and normal trucks are the scope of calculation, and the GHG emissions from diesel are not included in the number of 26,332 [k ton CO2] because diesel use is derived mostly from normal trucks. Second, the effects of new propulsion technologies such as battery electric vehicles and hybrid vehicles are estimated to be smaller in the fleet model than in the government calculation, which causes smaller GHG emission difference between these two scenarios in the fleet model. This is because fleet VKT is lower in the fleet model than in the government calculation. Third, the GHG emissions from electricity use are estimated to be higher in the fleet model than the government's calculation, which causes a smaller GHG emission difference between these two scenarios in the fleet model. In the fleet model, the average Japan grid mix is assumed to be constant in the future. In contrast, the government calculation expects a higher share of nuclear in electricity generation in the future, which means lower GHG emissions from electricity use. As was explained earlier, the share of nuclear in electricity generation is likely to become smaller in Japan because of the huge earthquake that occurred on March 11, 2011. Therefore, the result through 2030 from the fleet model should reflect actual vehicle usage better than the government calculation.

The sources of GHG emissions in each scenario are shown in Figure 30. In the Government Scenario, GHG emissions from electricity use will increase with the increase of the battery electric vehicles and plug-in hybrid vehicles. However, the increase of GHG emissions from electricity use is much smaller than the decrease of GHG emissions from gasoline use by 2030. In the Half of Government and the Realistic Scenarios, though some sales of battery electric vehicles and plug-in hybrid vehicles are expected, the GHG emissions from electricity use from both standard and light vehicles are much smaller than those from gasoline use. From these four graphs, it is clear that gasoline use has a great impact on the fleet GHG emissions. Therefore, the key to reducing the fleet GHG emissions is to reduce gasoline use.

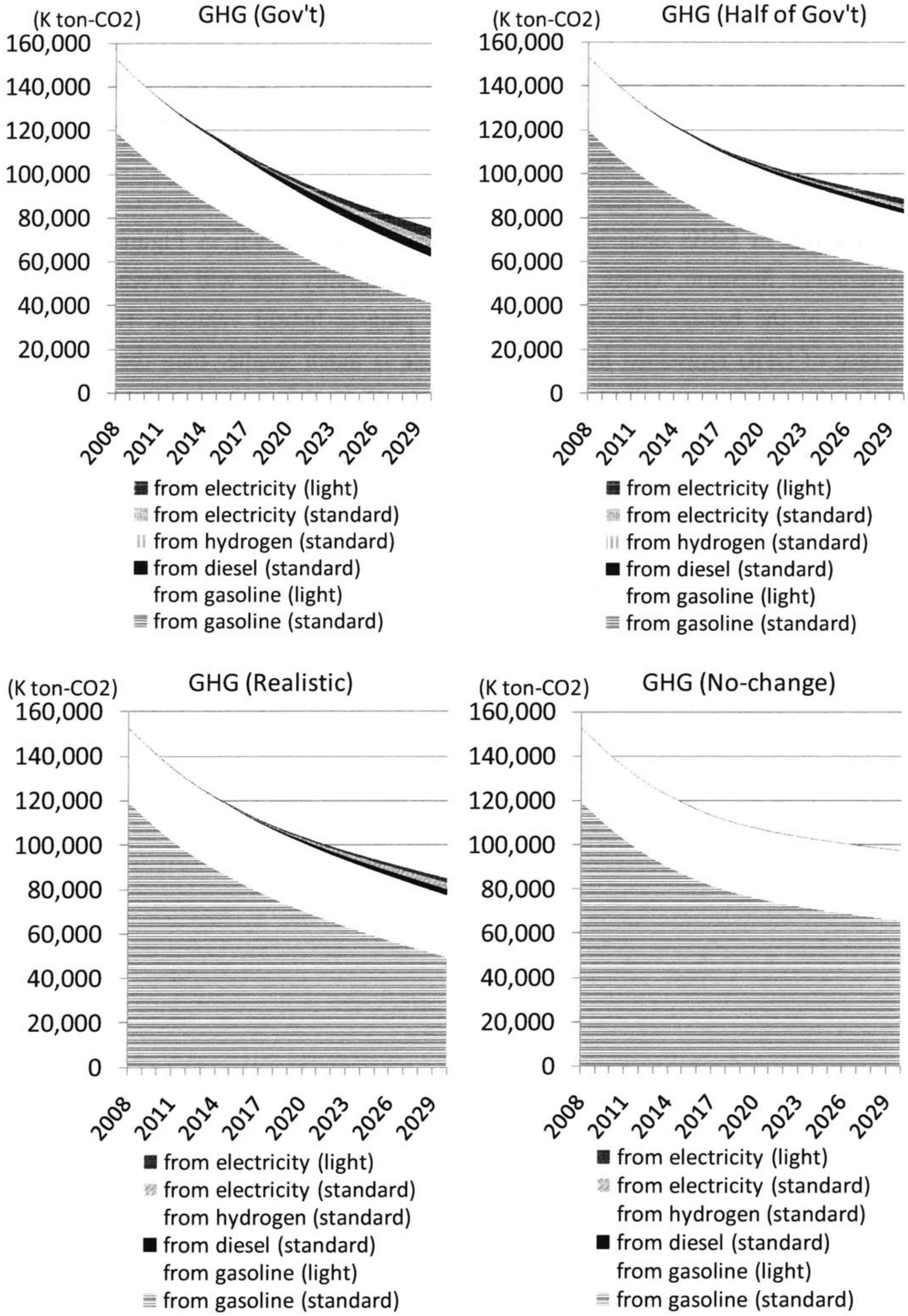


Figure 30. Fleet GHG emissions for each scenario

3.6 Fuel Use and GHG Emission Reduction Potential by Vehicle Weight Reduction

As shown in 2.2.6.2, there is a positive correlation between vehicle fuel consumption and vehicle weight. On average across all vehicle models in the U.S., every 100kg weight reduction will achieve a reduction of 0.53[L/100km] in fuel consumption [Cheah, 2010]. For all the model year 2008 passenger cars in Japan, every 100kg weight reduction is equal to 0.4[L/100km] reduction in fuel consumption in hybrid vehicles, 0.47 [L/100km] reduction in vehicles with CVT (continuously variable transmission), and 0.66[L/100km] reduction in fuel consumption in vehicles with AT (automatic transmission). Therefore, vehicle weight reduction in Japan has greater potential to reduce vehicle fuel consumption than in the U.S., although weight reduction is very difficult in Japan, where most vehicles are already small and light, as described below.

The trend of the average in-use vehicle weight in Japan is shown in Figure 31 [AIRIA, 2010]. Since the average weight of new light-duty vehicles sold in the U.S. was about 1,880kg in 2006 [Heavenrich, 2006], Japanese light-duty vehicles are much lighter, even when the difference between sales and in-use is taken into consideration. The average vehicle weights of compact trucks and compact passenger cars have been increasing in these twenty years. In contrast, the average vehicle weight of normal passenger cars has not changed.

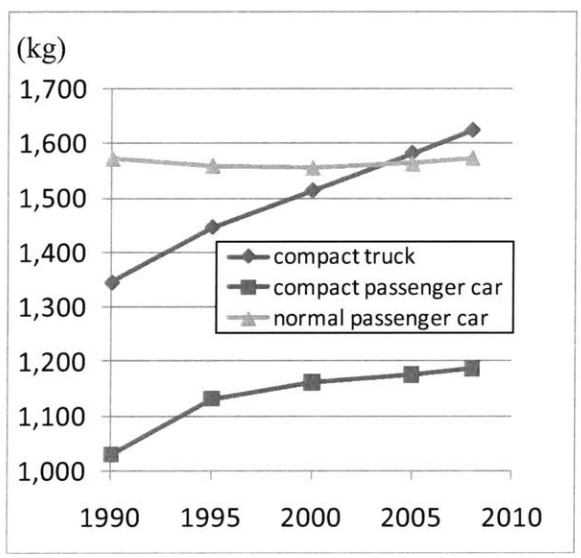


Figure 31. Average light-duty vehicle weight in Japan
[AIRIA, 2010]

In this way, even though the average vehicle weights are lighter in Japan than in the U.S., there is still some potential to reduce vehicle weights, especially for those vehicles which became heavier in these twenty years. For example, the fuel consumption of compact passenger cars (7.17[L/100km]) would be about 10% less (6.51[L/100km]) if the vehicle weight were 100kg smaller than the current vehicle weight, which is almost the same level as the vehicle weight of early 1990s. The relative fuel consumption data from the Ministry of Environment explained in 2.2.7.4 should have considered the effect of vehicle weight reduction to some extent (it is not clear what percentages of weight reduction were taken into consideration by the Ministry). However, it is clear that even in Japan, there is a certain amount of reduction potential in fuel use and GHG emissions through vehicle weight reduction.

4. LONGER-TERM FLEET FUEL USE AND GHG TRENDS (through 2050)

4.1 Objectives for Extending Timeframe to 2050

In contrast to the analysis through 2030 described in previous chapters, longer-term analysis is more difficult because it involves more uncertainties. However, there are several reports analyzing GHG reduction potential by 2050 in Japan as well as in the U.S. or other countries. For example, the Ministry of Environment has taken initiatives for a "research and development" project to explore the feasibility of reducing GHG emissions from fields such as transport, industry, and housing by 70% by 2050 from the level of 1990 [National Institute for Environmental Studies et al., 2007]. Since there is significant interest regarding the GHG emissions reductions by 2050, the longer-term fleet GHG emissions trend is also analyzed in this research.

4.2 Key Assumptions

Since the assumptions from 2030 to 2050 required for the fleet model are very difficult to forecast, very simple assumptions are made in the present research.

4.2.1 Assumptions for the Vehicle Fleet Modeling Part

The Vehicle fleet modeling part is composed of three inputs: vehicle sales, survival rate, and VKT.

<Vehicle sales>

Though the forecasts through 2030 show decreasing trends in all vehicle categories, vehicle sales forecasts from 2030 to 2050 are estimated to be constant in the present research. There are two reasons for this assumption. First, the population level, which affects vehicle sales, is likely to stabilize at some point even though the population of Japan has been getting smaller recently. Second, the decreasing sales trends are also unlikely to continue forever; vehicle sales are likely to become stable at some point. The assumed vehicle sales projected for each vehicle category from 2030 to 2050 are shown in Table 15.

Table 15. Annual vehicle sales projection (2030~2050) in Japan

	Annual vehicle sales (2030~2050)
Compact and normal passenger cars	2.7 million
K-cars	1.4 million
Compact trucks	0.15 million
K-trucks	0.46 million
All LDVs	4.7 million

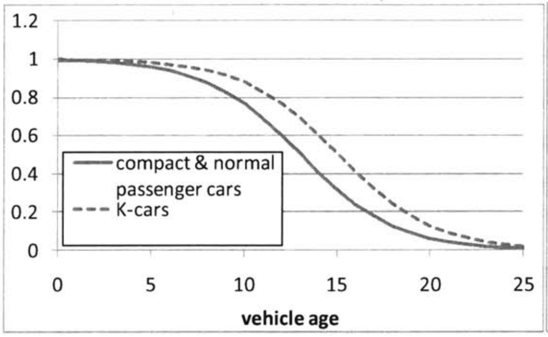
<Survival rate>

The survival rate of new vehicles is determined by using the logistic curve which requires the median lifetime (t_0) and a growth parameter (β), as explained in 2.2.3. Though the forecasts through 2030 show the increasing trends of median lifetime in all vehicle categories, the median lifetime forecast from 2030 to 2050 is estimated to be constant in the present research. This is because the increasing trends are unlikely to continue forever due to the heavy tax on old vehicles in Japan, and the median lifetime is likely to level off at some point. In fact, the government projected that the median lifetime was going to level off sooner than the present research projects [MOE, 2010]. The median life projection of each vehicle category from 2030 to 2050 is shown in Table 16.

Table 16. Assumed median lifetime (2030~2050) in Japan

	Median lifetime (2030~2050)
Compact and normal passenger cars	13.03 years
K-cars	15.06 years
Compact trucks	13.60 years
K-trucks	16.34 years

As for the growth parameter (β), β is kept constant after 2008, and this trend is assumed to continue toward 2050. Figure 32 shows the estimated survival rates of passenger cars (left) and light trucks (right).



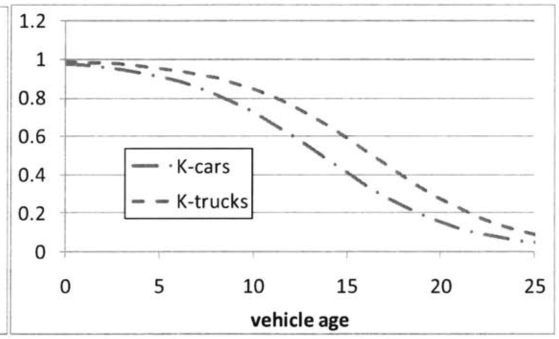


Figure 32. Estimated Survival Rates (model year 2030 onward)

<VKT>

Though the forecasts through 2030 show both the decreasing VKT trend for standard vehicles and the increasing VKT trend for light vehicles, VKT forecasts from 2030 to 2050 are estimated to be constant in the present research. This is because the decreasing or increasing trends are unlikely to continue forever, and VKT is likely to level off at some point. This view is also supported by the fact that no matter how important air travel becomes, buses, automobiles, and even low-speed trains will surely go on serving certain niches [Schafer and Victor, 1997]. The VKT projections from 2030 to 2050 are shown in Table 17.

Table 17. VKT per vehicle per year projection (2030~2050) in Japan

	VKT per vehicle per year
Standard vehicles	8,162[km]
Light vehicles	7,998[km]

4.2.2 Assumptions for the Scenario Analysis Part

The Scenario analysis part is composed of two inputs: sales mix scenarios and vehicle fuel consumption.

4.2.2.1 Sales Mix Scenarios

In the previous chapters, four scenarios were used to analyze through 2030. As explained in section 2.2.5, the Government Scenario might be too optimistic to be achieved. Therefore, the scenarios through 2050 developed in the present research are based on the Realistic Scenario before 2030, and then two potential future sales mix scenarios beyond 2030 were developed.

(1) Scenario A: little change beyond 2030

This scenario is the same as the Realistic Scenario shown in 2.2.5 before 2030, and assumes little change beyond 2030. Therefore, the sales share of each propulsion system in 2050 is estimated to be almost the same as in 2030. The details of Scenario A are shown in Table 18, Figures 33 and 34.

(2) Scenario B: greater change beyond 2030

This scenario is the same as the Realistic Scenario shown in 2.2.5 before 2030, and assumes greater change beyond 2030. Specifically, the sales share of plug-in hybrids and battery electric vehicles, which use electricity, is projected to be 50% in 2050. This 50% share target should be plausible because IEA developed the Electric and Plug-in Hybrid (EV/PHEV) Vehicles Roadmap to achieve by 2050 the widespread adoption and use of EVs and PHEVs, which together represent more than 50% of annual light-duty vehicle sales worldwide [IEA, 2009]. The details of Scenario B are shown in Table 19, Figures 33 and 34.

Table 18. Sales mix of Scenario A

Scenario A (standard)	%			
	2010	2020	2030	2050
Gasoline	82.10%	60.0%	35.0%	35.0%
Non-turbo (ICE)	*(82.10%)*	*(57.0%)*	*(31.5%)*	*(30.0%)*
Turbo gasoline		*(3.0%)*	*(3.5%)*	*(5.0%)*
Diesel				
Clean diesel	0%	3.0%	5.0%	5.0%
Gasoline hybrid	17.9%	20.0%	28.0%	30.0%
Strong hybrid				
Mild hybrid				
Micro hybrid				
Diesel hybrid	0%	2.0%	2.0%	0%
Electricity				
PHEV	0%	10.0%	20.0%	20.0%
BEV	0%	5.0%	10.0%	10.0%
Hydrogen				
FCV	0%	0%		0%
Scenario A (light)		%		
	2010	2020	2030	2050
Gasoline	99.42%	90.00%	75.00%	75.0%
Non-turbo (ICE)	*(84.51%)*	*(76.50%)*	*(63.75%)*	*(65.0%)*
Turbo Gasoline	*(14.91%)*	*(13.50%)*	*(11.25%)*	*(10.0%)*
Electricity				
BEV	0.58%	10.00%	25.00%	25.0%

Table 19. Sales mix of Scenario B

Scenario B (standard)	%			
	2010	2020	2030	2050
Gasoline	82.10%	60.0%	35.0%	20.0%
Non-turbo (ICE)	*(82.10%)*	*(57.0%)*	*(31.5%)*	*(12.5%)*
Turbo gasoline		*(3.0%)*	*(3.5%)*	*(7.5%)*
Diesel				
Clean diesel	0%	3.0%	5.0%	5.0%
Gasoline hybrid	17.9%	20.0%	28.0%	25.0%
Strong hybrid				
Mild hybrid				
Micro hybrid				
Diesel hybrid	0%	2.0%	2.0%	0%
Electricity				
PHEV	0%	10.0%	20.0%	30.0%
BEV	0%	5.0%	10.0%	20.0%
Hydrogen				
FCV	0%	0%		0%
Scenario B (light)		%		
	2010	2020	2030	2050
Gasoline	99.42%	90.00%	75.00%	50.0%
Non-turbo (ICE)	*(84.51%)*	*(76.50%)*	*(63.75%)*	*(40.0%)*
Turbo Gasoline	*(14.91%)*	*(13.50%)*	*(11.25%)*	*(10.0%)*
Electricity				
BEV	0.58%	10.00%	25.00%	50.0%

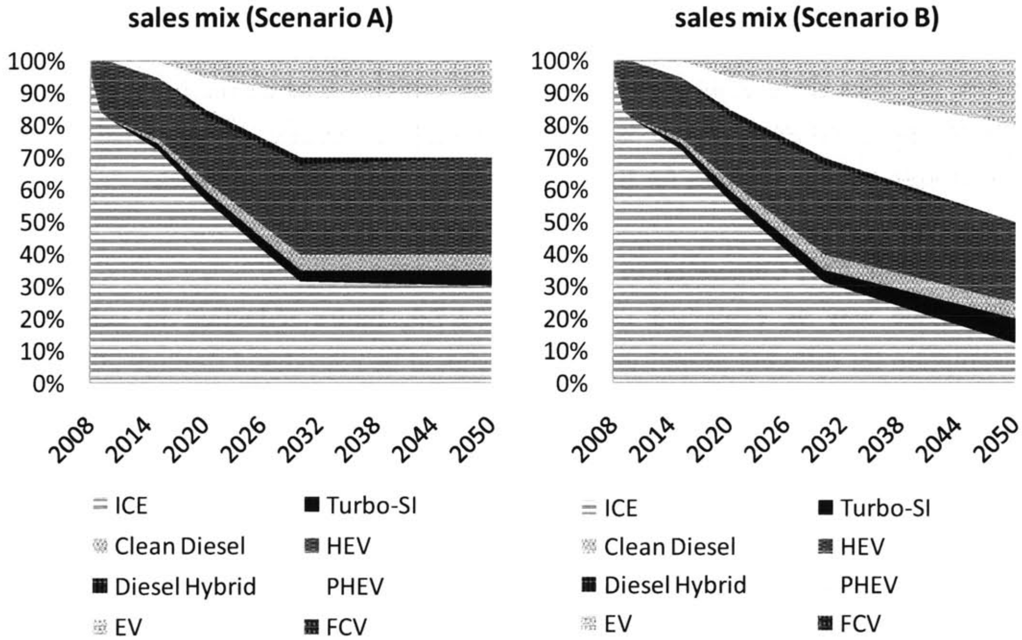


Figure 33. Sales mix scenarios for standard vehicles

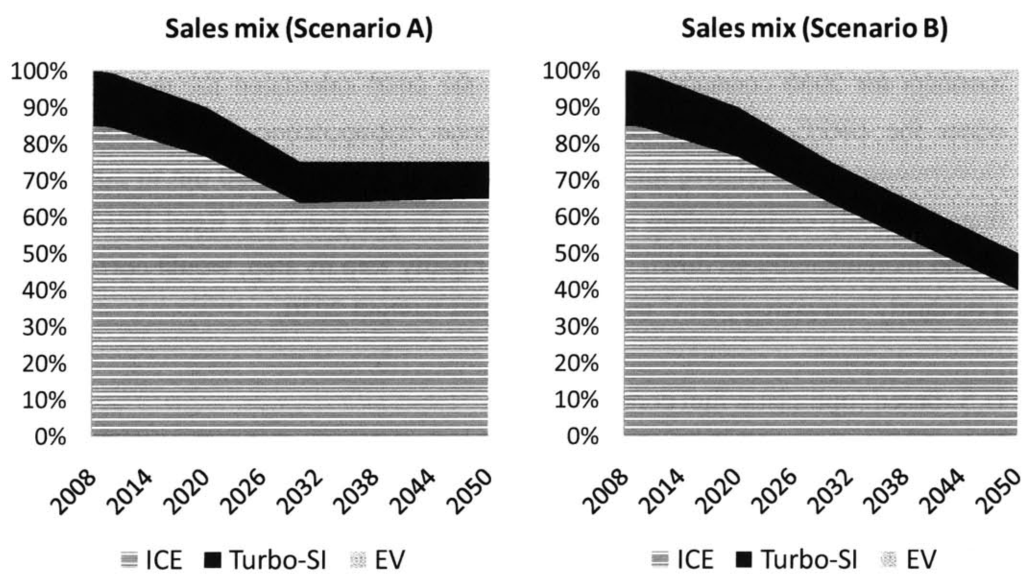


Figure 34. Sales mix scenarios for light vehicles

Figure 33 clearly shows that the small sales share of gasoline in 2050 for standard vehicles is achieved by the expanding share of plug-in hybrid and battery electric vehicles in Scenario B. In addition, Scenario B assumes less change after 2030 than before 2030. On the other hand, Figure 34 shows that Scenario B assumes almost the same speed of sales mix change before 2030 and after 2030 for light vehicles. This is because the sales share of conventional gasoline vehicles is projected to be still high in 2030 for light vehicles. There is more potential to replace conventional gasoline vehicles with electric vehicles for light vehicles than for standard vehicles.

4.2.2.2 Vehicle Fuel Consumption

In the same way as explained in section 2.2.7.4, future reduction in vehicle fuel consumption for different propulsion systems should be considered through 2050. Since no forecast for fuel consumption through 2050 is available from the Japanese government, two kinds of relative fuel consumption are developed in the present research.

(1) Government-based (conservative fuel consumption)

This forecast is based on the Japanese Government's forecast through 2030, which is used in section 2.2.7.4. It is the same as the relative fuel consumption shown in 2.2.7.4 before 2030, and the trend from 2020 to 2030 is extrapolated out to 2050. The details of the Government-based relative fuel consumption are shown in Figure 35. As mentioned in section 2.2.7.4, these Japanese Government fuel consumption numbers for 2030 correspond to numbers for 2030 calculated for the U.S. or EU when the ERFC is about 50%. This linear extrapolation of the trend in the Government-based relative fuel consumption from 2020 to 2030 out to 2050, rather than a steadily compounding trend (such as 2% per year at a fixed ERFC) which would incrementally go down slightly less rapidly step by step, would correspond to a modestly increasing ERFC trend above 50% beyond 2030.

(2) U.S.-based (optimistic fuel consumption)

This forecast is added to the present research because the Government-based relative fuel consumption is so conservative that it is not projected to change even in the next forty years. It is true that fuel consumption has already been lower in Japan than in the U.S. and will be difficult to improve. However, it is desirable to consider an optimistic fuel consumption forecast for the future like that in the U.S. The details of the U.S.-based relative fuel consumption are shown in Figure 36 [Bastani and Heywood, 2011]. These fuel consumption numbers for 2050 are close to 100% ERFC. Since the relative fuel consumption for hybrid diesel vehicles in the U.S. is not available, it is assumed in the present research to be the same as that for gasoline hybrid vehicles. In addition, the relative fuel consumption in 2020 is obtained by linear interpolation from the data of 2010 and 2030.

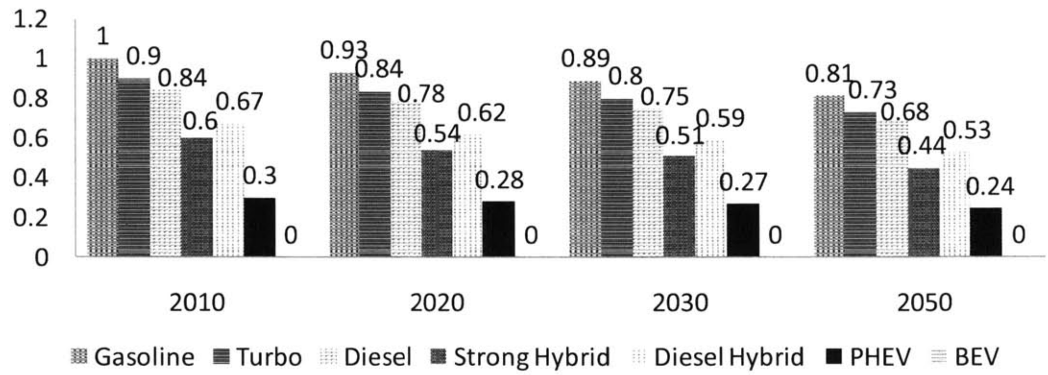


Figure 35. Relative fuel consumption for different propulsion systems (Gov-based)

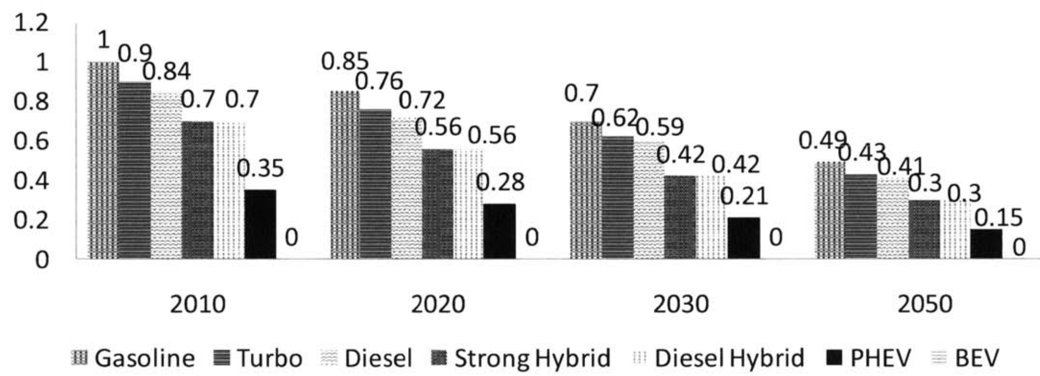


Figure 36. Relative fuel consumption for different propulsion systems (U.S.-based) [Bastani and Heywood, 2011]

Since the Government-based relative fuel consumption forecast assumes only modest change in the future, the gasoline consumption in 2050 in the Government-based forecast is almost the same as that in 2020 in the U.S.-based one.

4.3 Results

4.3.1 Vehicle Stock and Fleet VKT

In this section, the two results from the vehicle modeling part are explained.

<Vehicle stock>

Figure 37 shows the model calculated vehicle stock through 2050. As shown in Figure

37, vehicle stocks are forecast to be leveling off in all vehicle categories. Though this is calculated based on very simple assumptions, such as constant vehicle sales and median lifetimes after 2030, the vehicle stock trends will not be too different from the actual trends. The share of light vehicles is forecast to increase from 36% in 2009 to 43% in 2050.

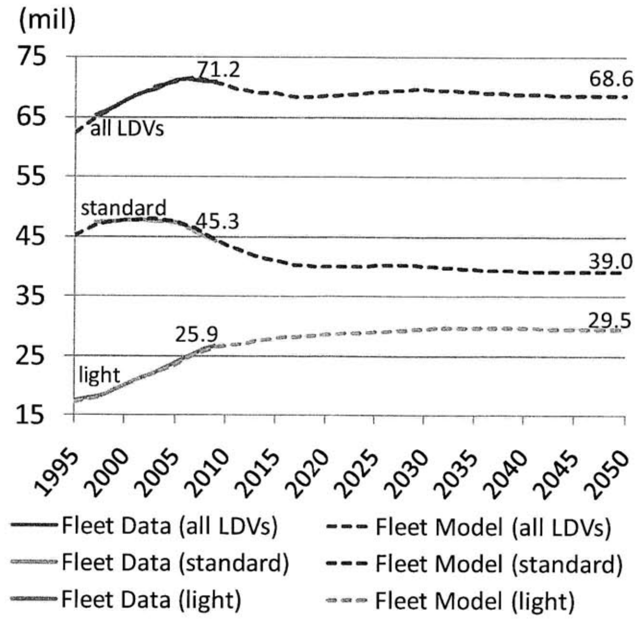


Figure 37. Vehicle stock through 2050
[AIRIA, 2010]

<Fleet VKT>

The Vehicle Kilometers Traveled calculated by the fleet model is shown in Figure 38. The total VKT for all light-duty vehicles is forecast to decrease by 18% from 2008 to 2050. The fleet VKT for standard vehicles in 2050 is projected to be 33% down from 2008. In contrast, the fleet VKT for light vehicles is forecast to increase by 17% in 2050 compared with the level in 2008, even though it is estimated to start decreasing after 2030. Due to the increasing trend of VKT for standard vehicles and the decreasing trend of VKT for light vehicles, the difference between VKT from standard vehicles and light vehicles is projected to become much smaller in 2050 than in 2008. Specifically, though the VKT from light vehicles was only 41% of that from standard vehicles in 2008, it is forecast to be 71% in 2050. Therefore, the share of VKT from light vehicles is projected to increase substantially in the future.

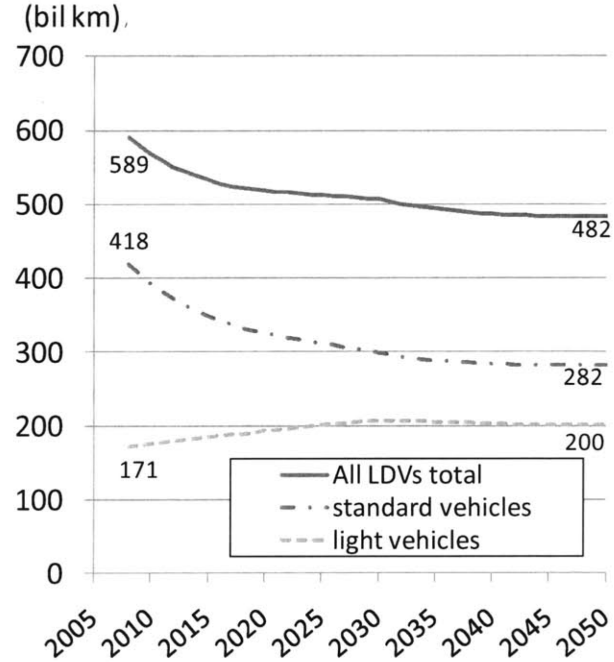


Figure 38. Total fleet VKT through 2050

From both Figures 37 and 38, the VKT from light vehicles is forecast to be 71% of the VKT from standard vehicles in 2050, and the share of light vehicle stock is forecast to be 76% in 2050. This is because the VKT per vehicle per year for light vehicles is assumed to be lower than that for standard vehicles in any year before 2050.

4.3.2 Fleet Fuel Use and GHG Emissions

In this section, the results about fuel use (including electricity use) and GHG emissions are explained.

<Fleet fuel use>

The results of the fleet fuel use from all light-duty vehicles in Japan are shown in Figure 39. C-A means "Conservative fuel consumption and Scenario A," and O-B means "Optimistic fuel consumption and Scenario B." Since diesel use is so small compared with gasoline use, another axis (at right) is used for diesel use so as to show the difference of each scenario. As Figure 39 shows, the fleet gasoline use is projected to decrease in the future in every case. In the O-B case, the fleet gasoline use in 2050 is 75% less than in 2008. Even in the C-A case, the fleet gasoline use in 2050 is 60% less than in 2008. In this last case, fleet fuel use is projected to continue to decrease through

2050, even though the fuel mix scenario does not change so much after 2030. There are two reasons. First, even though it is modest, fuel consumption of each propulsion system is projected to continue improving. Second, the fleet VKT of all LDV is projected to decrease even after 2030. As for diesel use, it is assumed to decrease in the 2030s, which comes from the declining sales of hybrid diesel vehicles. Since it is not clear whether diesel hybrid is going to be popular in Japan in the future, the sales of diesel hybrid in both Scenarios A and B were projected to decrease from 2% in 2030 to 0% in 2050. In addition, because the sales mix for clean diesel vehicles and diesel hybrid vehicles are exactly the same in Scenarios A and B, the results of fleet diesel use from the C-A and C-B cases are the exactly the same, as are the O-A and O-B cases.

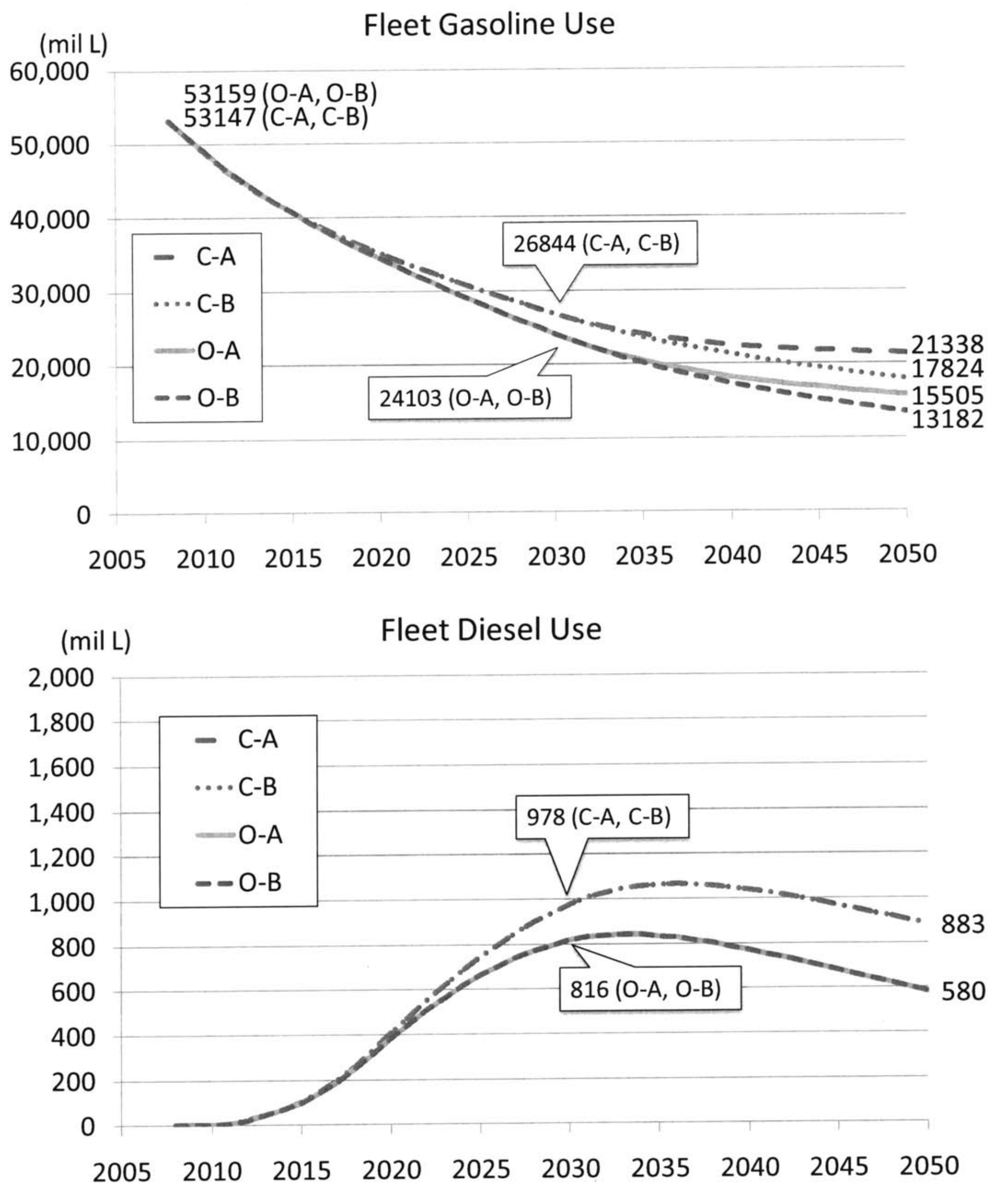


Figure 39. Fleet fuel use through 2050

In 2008, the fleet fuel use is higher in the O-A and O-B cases than the C-A and C-B cases. This is because of the different assumptions of relative fuel consumption. In the Government-based (conservative) fuel consumption forecast, gasoline hybrid (shown as "strong hybrid" in Figure 35) is assumed to be 0.6 in 2010 and before. On the other hand, in the U.S.-based (optimistic) fuel consumption forecast, gasoline hybrid (shown as "strong hybrid" in Figure 36) is assumed to be 0.7 in 2010 and before. These numbers of 0.6 and 0.7 are relative to gasoline fuel consumption (1.0) in 2010.

In Figure 39, the decrease in the C-B case after 2030 seems to be larger than that in the O-A case after 2030. However, if the decrease is compared by the percentage after 2030, the O-A case changes a little bit more than the C-B case. Specifically, the fleet gasoline use in 2050 is 34% down from that in 2030 in the C-B case. On the other hand, the fleet gasoline use in 2050 is 35% down from that in 2030 in the O-A case. In this way, both the sales mix change and the relative fuel consumption improvement are very important to reduce fleet fuel use in the future.

Figure 40 shows the fleet fuel use by standard vehicles and light vehicles in each case. The large reduction of gasoline use comes from the decrease of gasoline use by standard vehicles. In the O-B case, the fleet gasoline use by standard vehicles in 2050 is 20% of that in 2008, and the gasoline use by light vehicles in 2050 is 46% of that in 2008. In the C-A case, the fleet gasoline use by standard vehicles in 2050 is less than one-third of that in 2008, and the gasoline use by light vehicles in 2050 is about 72% of that in 2008. Hence, substantial fuel use reduction is projected to be achieved because of the decrease of gasoline use by standard vehicles.

Though the C-A and O-A cases project little change in the sales mix after 2030, the fleet gasoline use from both standard and light vehicles is projected to decrease after 2030. This is projected because the fleet VKT from both standard and light vehicles is envisaged to decrease after 2030, and because the fuel economy of each propulsion system is projected to continue improving. In the O-B case, the fleet gasoline use by standard vehicles in 2050 is 47% down from that in 2030, and the fleet gasoline use by light vehicles in 2050 in 39% down from that in 2030. In the C-A case, the fleet gasoline use by standard vehicles in 2050 is 24% down from that in 2030, and the fleet gasoline use by light vehicles in 2050 is 14% down from that in 2030. In the C-B and O-A cases, the total fleet gasoline use reduction is by about 35% from the level of 2030 by 2050. However, the gasoline reduction trends are different in each case. Specifically, the gasoline use reduction from standard vehicles by 2050 from the level of 2030 is smaller in the C-B case than in the O-A case. On the other hand, the gasoline use reduction from light vehicles by 2050 from the level of 2030 is larger in the C-B case than in the O-A case.

As for diesel use, the trends look the same in all the cases because the amount of diesel use is much smaller than that of gasoline use. In contrast to gasoline use, neither the sales mix scenario nor fuel consumption forecast makes diesel use change significantly.

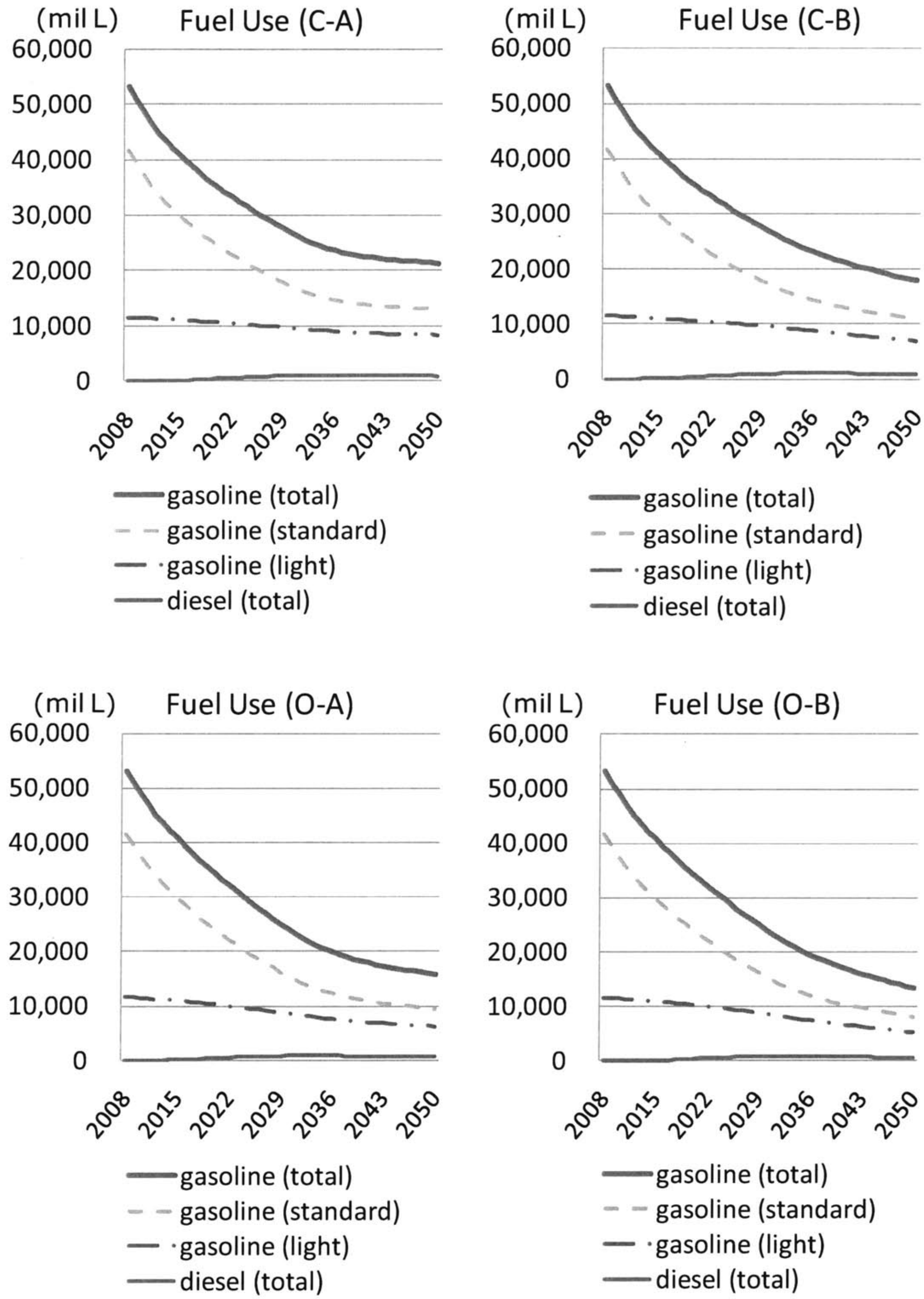


Figure 40. Fleet fuel use through 2050 for each case

<Fleet electricity use>

The result of the fleet electricity use from all light-duty vehicles in Japan is shown in Figure 41. Since fleet electricity use depends not on the relative fuel consumption forecast but on the fuel mix scenario such as Scenario A and Scenario B, the results of fleet electricity use from the C-A and O-A cases are the exactly the same, as are the C-B and O-B cases. The fleet electricity use in the C-B and O-B cases increases more than in the C-A and O-A cases because of the larger sales share of battery electric vehicles and plug-in hybrid vehicles. Since 1,000 GWh of electricity is equivalent to 104 million liters of gasoline in chemical energy[5], 23,504 GWh of electricity is equivalent to about 2,450 million liters of gasoline in chemical energy.

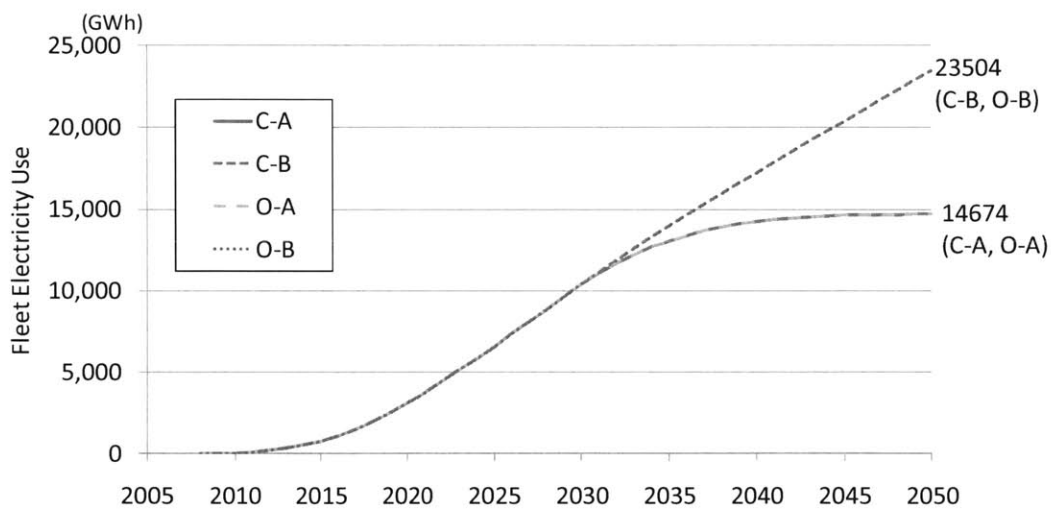


Figure 41. Fleet electricity use through 2050

Figure 42 shows the fleet electricity use from standard vehicles and light vehicles in each scenario. The trends of the fleet electricity use from standard vehicles and that from light vehicles are similar in all cases. In the C-A and O-A cases, the fleet electricity use from both standard and light vehicles is projected to increase and level off because the sales mix scenarios for both standard and light vehicles do not change after 2030. In the C-B and O-B cases, the fleet electricity use from both standard and light vehicles is projected to increase. This is because the sales mix scenario B for light

[5] Gasoline: 1[L] = 34.6 [MJ], Electricity: 1[kWh] = 3.6 [MJ],
Therefore, 1,000 [GWh] (electricity) = $3.6*10^9$ [MJ],
which is equivalent to $3.6*10^9$ [MJ] / 34.6 [MJ] = 104.0 [mil L] (gasoline).

vehicles after 2030 assumes as many changes as that before 2030, and because the sales mix scenario B for standard vehicles still assumes some sales mix change beyond 2030. The percentage of the fleet electricity use from light vehicles increases from 40% in 2030 to 42% in 2050 in the C-A and O-A cases, and to 45% in 2050 in the C-B and O-B cases. These trends are consistent with the following two assumptions. First, the Japanese fleet is projected to be shifting from standard vehicles to light vehicles. Second, in the sales mix scenario B, vehicle electrification is likely to happen more rapidly after 2030 in the light vehicles.

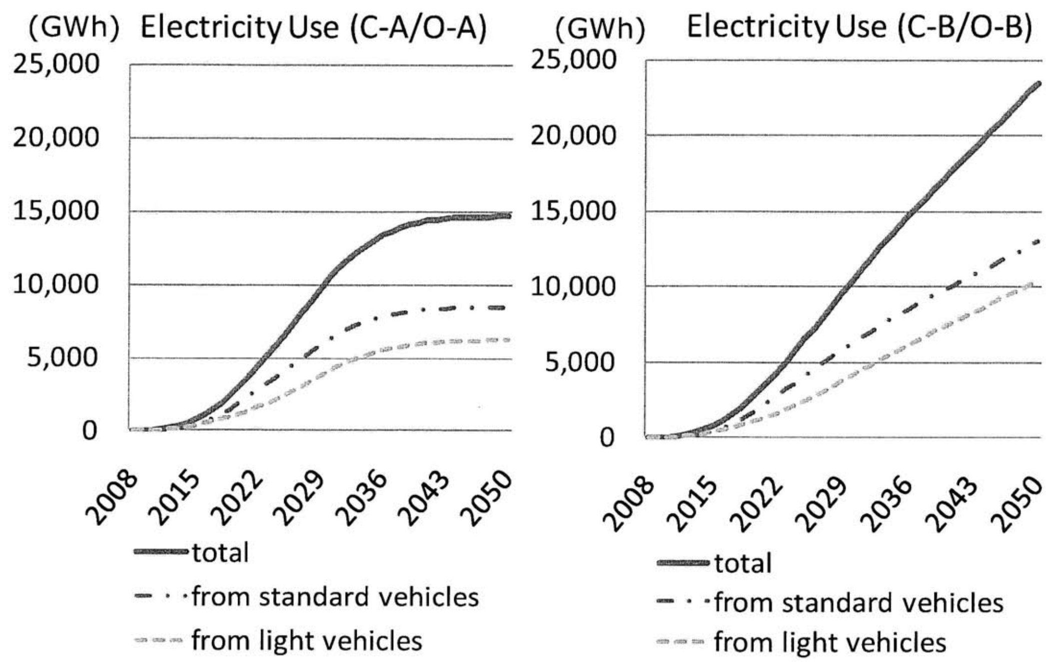


Figure 42. Fleet electricity use through 2050 for each case

<Fleet GHG emissions>

Figure 43 shows the result for the fleet GHG emissions. The upper four lines are fleet GHG emissions from total light-duty vehicles (both standard and light vehicles.) The middle four lines are fleet GHG emissions from standard vehicles. The lower four lines are fleet GHG emissions from light vehicles. GHG emissions are calculated on a well-to-wheel basis by multiplying the fuel use by a corresponding well-to-tank and tank-to-wheel greenhouse gas emissions coefficient, as explained in section 3.5. In the present research, the GHG emissions from the Japanese electricity grid are projected to be constant in the future for the same reasons explained in section 3.5.

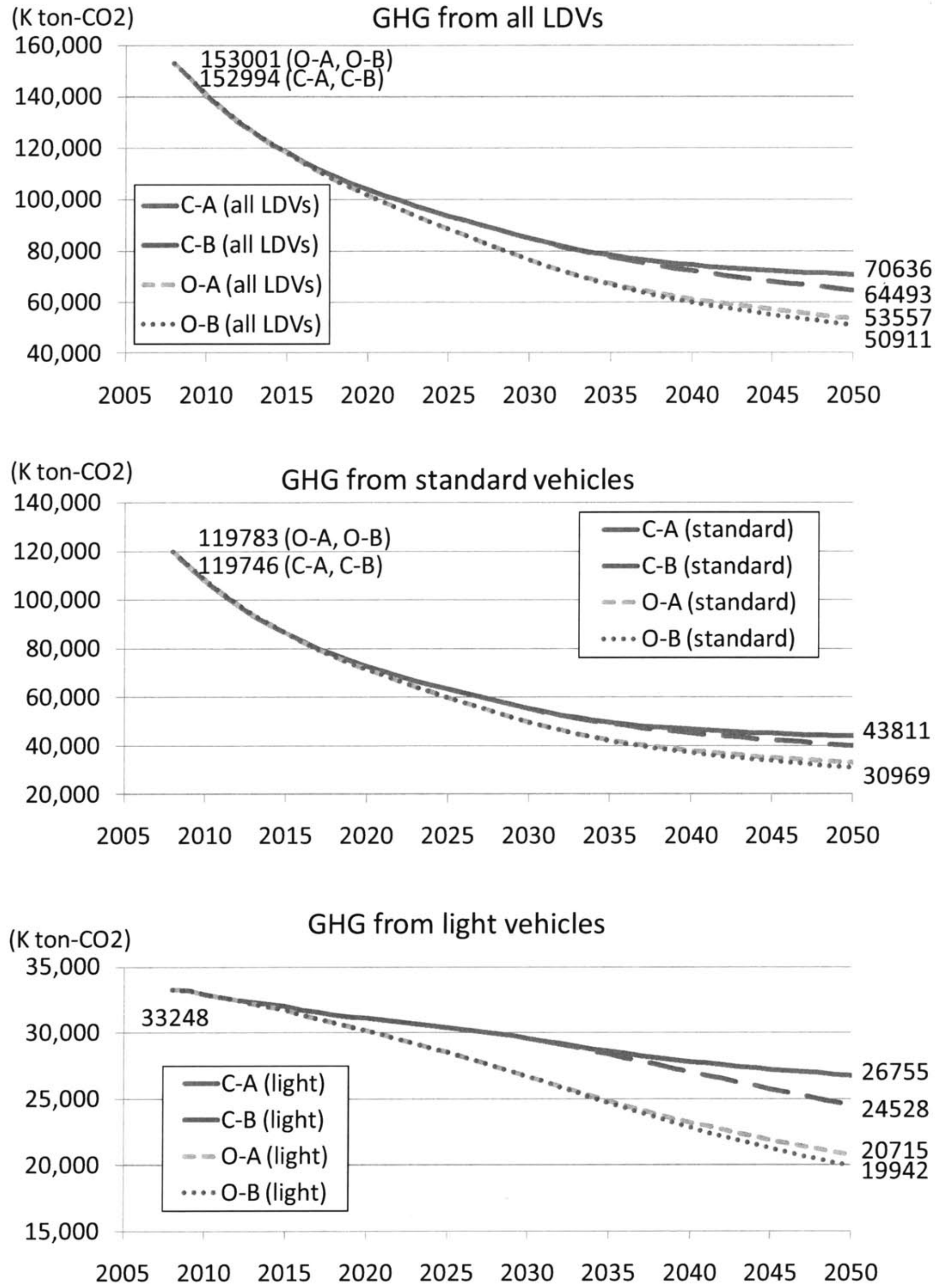


Figure 43. Fleet GHG emissions through 2050

In the O-B case, the total fleet GHG emissions in 2050 are one-third of those in 2008. Even in the C-A case, the total fleet GHG emissions in 2050 are less than half of those in 2008. These big reductions are due to the decrease of fleet GHG emissions from standard vehicles. In the O-B case, the fleet GHG emissions from standard vehicles in 2050 are about 75% down from those in 2008. In the No-change Scenario, the fleet GHG emissions from standard vehicles in 2050 are 63% down from those in 2008.

As for light vehicles, the fleet GHG emissions in 2050 are about 42% down from those in 2008 in the O-B case, and 20% down in the C-A case. The fleet GHG emissions reduction from light vehicles is smaller than from standard vehicles. There are two possible reasons. First, the fleet VKT for light vehicles is not going to decrease from the level in 2008 because it is projected to increase until 2030 and to decrease after that. Second, the sales mix change for light vehicles is projected to be smaller than that for standard vehicles. Even in 2050, the share of conventional gasoline vehicles is high, especially in Scenario A. In addition, new propulsion systems such as hybrid or plug-in hybrid are not projected to be sold in light vehicles.

Overall, the trends of fleet GHG emissions are similar to those of fleet gasoline use because fleet electricity use has less impact on GHG emissions compared with fleet gasoline use.

The sources of GHG emissions in each scenario are shown in Figure 44. In all cases, GHG emissions from electricity use are projected to increase with the increase of the battery electric vehicles and plug-in hybrid vehicles. However, the increase of GHG emissions from electricity use is much smaller than the decrease of GHG emissions from gasoline use by 2050. The percentage of GHG emissions from electricity use in 2050 differs from one case to another; the largest is 21% in the O-B case, and the smallest is 9% in the C-A case. From these four graphs, it is clear that gasoline use has a greater impact on the fleet GHG emissions than the fleet electricity use. Therefore, the key to reducing the fleet GHG emissions is to reduce gasoline use.

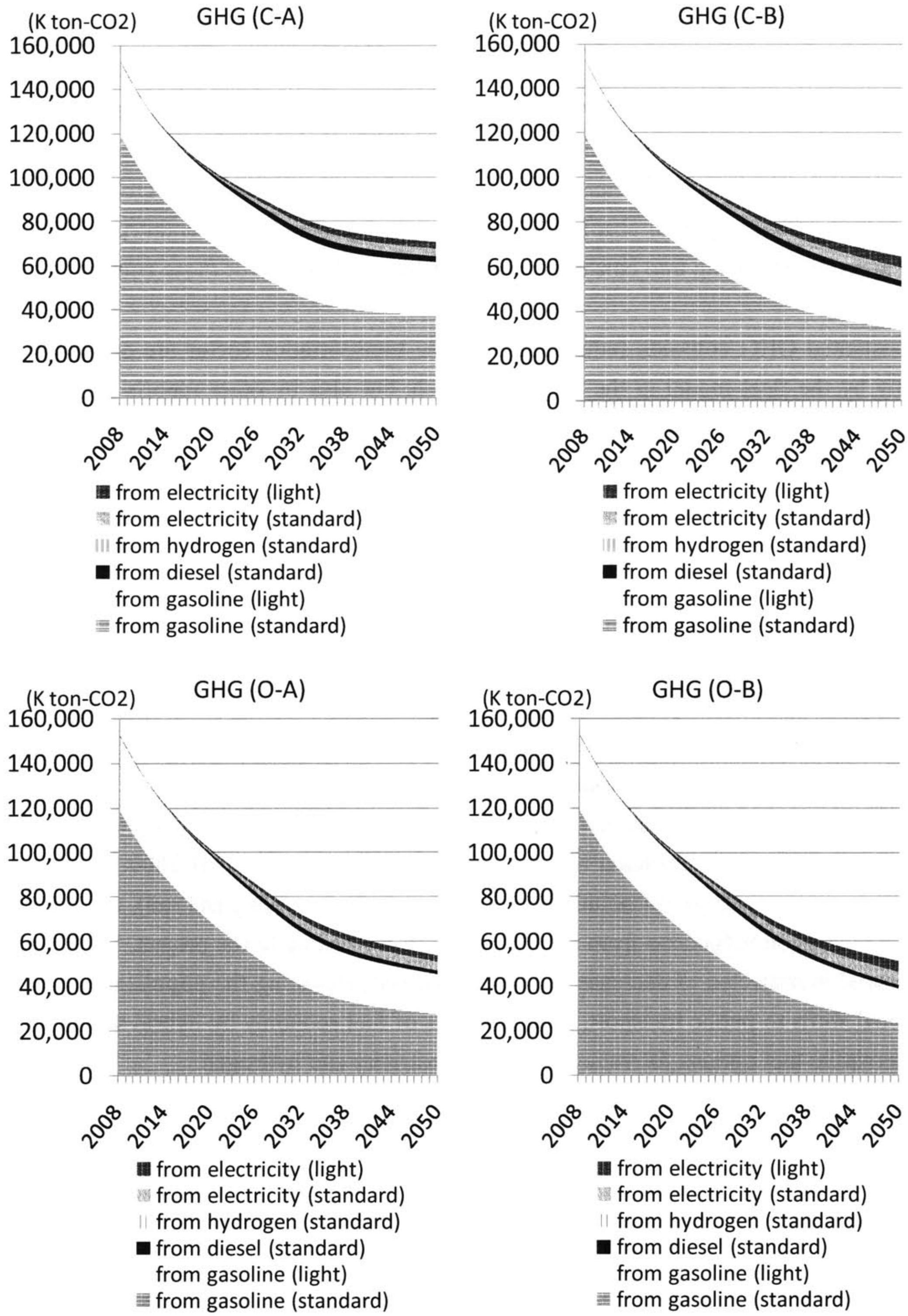


Figure 44. Fleet GHG emissions through 2050 for each case

5. DISCUSSION

The GHG emission reduction potentials by 2050 obtained by the fleet model are much more substantial in Japan than those in other countries such as the U.S. and EU. It is important to keep in mind that GHG emissions are projected to decrease in Japan even without any efforts to change incentives or improve technology, simply because of the demand decline of road transportation. Therefore, comparing the GHG emission reduction potentials in an absolute sense between Japan and other countries might not be appropriate, taking into consideration the different situations of those countries.

Substantial GHG emission reductions from the transportation sector are projected, not only by the fleet model in the present research, but also by other reports on reducing GHG emissions, and the Japanese Government considers such reductions to be feasible. The questions are what amounts of GHG emission reductions are expected by the Japanese Government to be achieved, and what effective measures would be effective to achieve them.

5.1 GHG Emission Reductions Expected by the Government

As mentioned in Section 4.1, the Ministry of Environment has taken initiatives for a "research and development" project to explore the feasibility of reducing GHG emissions from fields such as transport, industry, and housing by 70% by 2050 from the level of 1990 [National Institute for Environmental Studies et al., 2007]. This project concluded that such a substantial amount of GHG emission reduction would be possible. In detail, 80% GHG emission reductions by 2050 from the level of 2000 are assumed from passenger transport (including road transport, air transport, and rail), and 60~70% GHG emission reductions from freight transport. According to the project, the transport demand is projected to decrease for several reasons, including the population decrease, modal shifts to public transport, improvements of fuel economy by hybrid vehicles, and alternative fuel options for vehicles such as electricity and hydrogen.

It is difficult to compare the results from the Government-initiated projects with those from our research. Our present research scope is light-duty vehicles and does not include heavy-duty vehicles, rail, or air transport; and also, our research focus is on the GHG emission reductions from the level of 2008, not the level of 2000 or 1990. Roughly speaking, however, GHG emissions from light-duty vehicles are projected to decrease more than 70~80% from the level of 2008.

5.2 Effective Measures for Substantial GHG Emission Reductions

As stated above, substantial GHG emission reductions in Japan by 2050 are expected and considered to be feasible. The present research as well as the Government-initiated project assumes that road transport demand will decline and the fleet VKT is going to become smaller in the future. In the present research, the C-A case, which assumes modest change through 2050 (See chapter 4), does not project enough GHG emission reductions. Even in the O-B case, GHG emission reductions from light-duty vehicles by 2050 are less than 70% from the level of 2008. As was mentioned in section 4.2.2.2, the relative fuel consumption forecast for the O-B case is a U.S.-based number and may be difficult to achieve in Japan, where fuel consumption has already been much lower than that of other countries. Taking these into consideration, the following two factors are important to reduce GHG emissions by substantial amounts. First is an optimistic fuel mix scenario, such as the Government Scenario explained in section 2.2.5. Second is an optimistic relative fuel consumption forecast, such as the U.S.-based one explained in section 4.2.2.2. Some effective measures for achieving substantial GHG emission reductions from the light-duty vehicle fleet are explained below.

(1) *Subsidies or tax cuts for new propulsion technology vehicles such as hybrid vehicles*

The effectiveness of this measure has already been proved recently. The sales share of hybrid vehicles of compact and normal passenger cars increased from 4.4% in 2008 to 15.6% in 2009 in Japan. This was achieved because of the "Tax Cuts for Eco-cars" policy implemented by the Japanese Government from April 1st, 2009 to September 7th, 2010. Eco-cars are defined as low-emission vehicles such as hybrid vehicles and battery electric vehicles. This policy required JPY 583.7 billion of the government budget. Under this policy, eco-cars that met the standards of emissions and fuel economy set by the Japanese Government, received exemption from or reduction of the vehicle acquisition tax, vehicle weight tax, and vehicle tax. The details of the tax cuts are shown in Table 20.

Table 20. Tax cuts for eco-cars
[Road Transport Bureau, MLIT, 2011; NAVI, 2011; TMG, 2008]

	Eco-cars	Non eco-cars (K-cars)	Non eco-cars (compact & normal passenger cars
Vehicle acquisition tax (when purchased)	100% exemption	3% of the car price	5% of the car price
Vehicle weight tax (every 2 years)	100% exemption (once)	JPY 7,600	JPY 10,000~60,000 (Depending on vehicle weight)
Vehicle tax (every year)	About 50% exemption (once)	JPY 7,200	JPY 29,500~111,000 (Depending on displacement)

Suppose that a person wants to purchase a new passenger car. The vehicle price is JPY 2 million, the vehicle weight is 1.5t, and the displacement is 1799cc. Without tax cuts for eco-cars, the total tax paid in the first 3 years would be JPY 295,500. However, owing to the tax cuts for eco-cars, the total tax paid in the first 3 years would be only JPY 153,500. In this case, JPY 142,000 is saved [Honda, 2010].

Therefore, this kind of financial incentive makes more likely to occur an optimistic fuel mix scenario such as the Government Scenario.

(2) Improving infrastructures for electric vehicles and plug-in hybrid vehicles

In order to make battery electric vehicles and plug-in hybrid vehicles more prevalent in the future, improving infrastructures for these vehicles is essential. Though Toyota and some Japanese auto manufacturers have developed plug-in hybrid or battery electric vehicles, the limited infrastructures for providing electricity to charge the vehicles are bottlenecks for their sales growth. Therefore, improving infrastructures for these vehicles is an essential and effective measure to increase the sales share of battery electric vehicles and plug-in hybrids.

(3) Higher taxes on older vehicles such as vehicles aged 15 years and over

This measure might be effective for urging drivers to get new vehicles, rather than for achieving an optimistic fuel mix scenario. However, the basic concept of increasing the share of vehicles with new propulsion systems in Japanese light-duty vehicles is the same. As Figure 7 shows, the average lifetime has been getting longer and longer, especially after 1996. If this trend continued, people would not purchase new vehicles as much, and the share of new vehicles such as hybrid and battery electric vehicles would be difficult to increase. However, if higher taxes were imposed on older vehicles, such as those 15 years old or older, more incentive to purchase new vehicles with better fuel economy would exist.

(4) Vehicle weight reductions

This measure should be effective for achieving the optimistic relative fuel consumption forecast close to the U.S.-based one. As for all model year 2006-2008 light-duty vehicles offered in the U.S., every 100kg weight reduction will achieve a reduction of 0.53L/100km in fuel consumption [Cheah, 2010]. On the other hand, as for model year 2008 passenger cars with AT (Automatic Transmission) offered in Japan, every 100kg weight reduction will achieve a reduction of 0.66L/100km in fuel consumption. The difference arises because the test cycles are different in the U.S. and Japan. In this way, vehicle weight reductions have greater impacts on fuel consumption in Japanese passenger cars, even though further vehicle weight reductions are hard to achieve.

6. CONCLUSIONS

The present research has been implemented to forecast and analyze fuel use and GHG emissions from light-duty vehicles in Japan, by using the fleet model. The following conclusions can be drawn from the present research.

1. The potential for reducing fuel use and GHG emissions from the total light-duty vehicle fleet is substantial. In the Government Scenario, a 49% GHG emission reduction from the level of 2008 is achieved by 2030. In the Realistic Scenario, a 45% GHG emission reduction is achieved by 2030. Even in the No-change Scenario, in which the sales mix is constant in the future, GHG emissions in 2030 are down 36% from those in 2008.

2. There are three possible reasons for the substantial fuel use and GHG emission reductions. First, vehicle sales and VKT for standard vehicles are decreasing. Second, even in the case of the No-change Scenario, mainstream gasoline vehicle technology is projected to improve. Third, there seems to be a trend from standard vehicles toward light vehicles for several reasons such as lower taxes and better fuel economy of light vehicles.

3. In the longer-term analysis, a 67% GHG emission reduction from the level of 2008 is achieved by 2050 in the O-B case, which assumes the optimistic relative fuel consumption forecast and greater sales mix change. Even in the C-A case, which assumes the conservative relative fuel consumption change and little sales mix change, a 54% GHG emission reduction from the level of 2008 is achieved by 2050. These big reductions are due to the decrease of fleet GHG emissions not from light vehicles but from standard vehicles.

4. GHG emission reduction trends are similar to fleet fuel use reduction trends because the growth in electricity is modest and the impact of fuel use is dominant. Therefore, the most important thing for GHG emission reductions is how to reduce fleet fuel use.

5. There are two key factors which enhance the fleet fuel use and GHG emission reduction potential in the future. The first one is achieving optimistic fuel mix scenario targets, as in the Government Scenario. The second one is achieving optimistic relative fuel consumption levels, such as in the U.S.-based forecast.

Therefore, several effective measures concerned with these key factors would be important to apply.

GHG emission reduction involves not only technical breakthroughs but also some social factors, such as demand declines. Though substantial GHG emission reduction potential from light-duty vehicles in Japan is projected by 2050, coordinated policy measures could help to achieve even further GHG emission reductions.

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