Chapter 9

# Understanding Fuel Consumption/Economy of Passenger Vehicles in the Real World

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Additional information is available at the end of the chapter

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## 1. Introduction

The world is currently highly dependent upon oil for automotive transport. As a result, large amounts of greenhouse gas (GHG) emissions are generated in the passenger automotive sector and are having a substantial effect on the environment. Among the various measures from both the automotive technology side and the transport demand side to reduce energy consumption and GHG emissions, improving the fuel consumption (FC, expressed in litres of gasoline per hundred kilometres of travel [L/100 km]) or fuel economy (FE, usually expressed in [km/L] or miles per gallon [mpg]) of passenger vehicles is regarded as the most effective measure. In this regard, many regions and countries around the world have implemented FC/FE or GHG standards (An et al., 2011), and some — for example, the United States, the European Union, and Japan — are tightening their existing standards.

FC/FE and GHG standards are measured by using chassis dynamometer test cycles, which simulate a variety of driving conditions at typical highway and urban driving speeds in each country and region. However, it is quite well known that a gap exists between FC/FE values generated by dynamometer testing and real-world values worldwide (Schipper & Tax, 1994; Schipper, 2011). Real-world FC/FE values depend strongly upon each driver's style and location, upon the traffic congestion, weather, and corresponding use of accessories (especially air conditioning), and upon the vehicle's maintenance condition. No single test cycle can simulate all possible combinations of these factors. Although the energy roadmaps and CO2 reduction targets for the passenger automotive sector in each region and country are based mainly on FC/FE and GHG standards, it is the real-world values that matter. It is doubtful whether reduction targets can be met without more accurate real-world assessments of FC/FE and GHG emissions. Providing more accurate real-world FC/FE values will also better inform consumers of expected fuel costs.

The many studies that have investigated FC/FE and GHG emissions in the real world have used several approaches. Schipper (2011) analysed FC trends for the entire passenger vehicle fleet in the United States, Australia, Japan, and several European countries by using national or regional statistics, as well as the impact of fuel prices upon FC/FE. Wang et al. (2008) explored the influence of driving patterns on FC in China by using a portable emissions measurement system and established an on-road FC estimation model. Duoba et al. (2005) tested the robustness of FE to changes in vehicle activity for hybrid vehicles (HVs) and their counterpart internal combustion engine vehicles by applying various driving schedules upon a chassis dynamometer in the U.S. Several studies have also analysed on-road FC/FE by using information collected by questionnaires or on the internet. Huo et al. (2011) examined the differences between standard test and real-world values for Chinese passenger vehicles by using data voluntarily reported by drivers on the internet; the study gathered 63,115 pieces of real-world FC data for 153 vehicle models. Sagawa & Sakaguchi (2000) analysed the FE of Japanese passenger vehicles using questionnaires, but they were unable to analyse the data with high statistical reliability because of sample number limitations (1,479 samples).

The use of internet-connected mobile phones has become widespread throughout the world, and the range of mobile phone contents and services provided includes those used to track the FC/FE of automobiles. In order to analyse real-world FC/FE in Japan with a high level of statistical reliability, the author's group put focus upon the FC/FE management service in which voluntarily reported FC log data of the vehicle users are collected through internet-connected mobile phones across Japan and developed and on-road (actual) FC database. The findings for the 24 months from October 2000 to September 2002 are reported by Kudoh et al. (2004).

Since 2000, the number of brand-new passenger vehicles sold in Japan has fluctuated between 4.26 and 4.76 million, which means that about 8% of the total passenger vehicle fleet was replaced with brand-new vehicles annually. Since the FC/FE of brand-new vehicles improved during this period, it is reasonable to conclude that the FC/FE performance of the passenger vehicle fleet itself should also have improved as these new vehicles replaced older ones. In addition, the mobile phone service provider whose log data were used to develop the actual FC database has reported an increase in the number of users in the 2000s.

The author's group therefore updated the database by extending the data collection period from 24 to 54 months and created a database consisting of 1,645,923 pieces of log data collected from October 2000 through March 2005, including information from 49,677 passenger vehicle users on 2,022 models sold in Japan and conducted a statistical analysis of actual FC for passenger HVs and other passenger vehicles with internal combustion engine in Japan (Kudoh et al., 2007; Kudoh et al., 2008). In addition to the previous achievements of the author's group, this paper addresses the effects of vehicle specifications towards the actual FC/FE of passenger vehicles in Japan, as derived from the database, from a statistical point of view.

## 2. Reasons for the FC/FE measurement gap

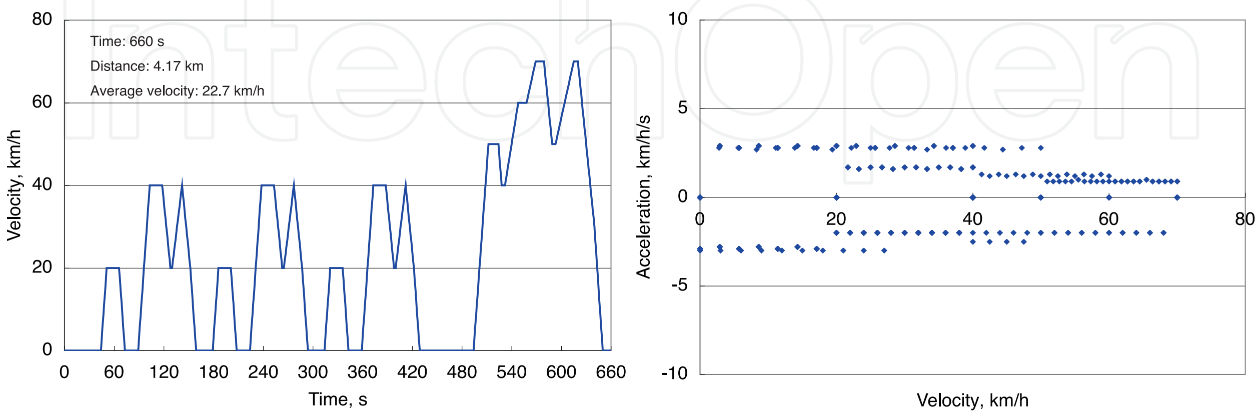
In Japan, targets for FE standards are provided in the revised Law Concerning the Rational Use of Energy (known as the Energy-Saving Law) by implementing the "Top Runners

Approach," which aims to establish energy-efficiency standards that meet or exceed the best energy-efficiency specifications for a product in an industry.

According to the revised law, passenger vehicles sold on the Japanese market in 2010 were expected to achieve the FE standard stipulated in the Japanese 10-15 mode driving schedule for each vehicle inertia weight class. The 10-15 mode driving schedule was developed for exhaust measurement and FE tests of light duty vehicles in Japan, including passenger vehicles; the driving pattern and relationship between velocity and acceleration are shown in Figure 1. The test is conducted on a chassis dynamometer with a hot start at curb weight plus 110 [kg] (the approximate weight of 2 passengers), with the air conditioner and other electrical appliances turned off. Figure 2 shows an example of actual vehicle travel activity measured in an urban area (TMGBE, 1996); the average velocity is almost the same in both figures. Although the 10-15 mode driving schedule is supposed to represent actual vehicle travel activity within Japanese urban areas, acceleration and deceleration occurred more frequently under actual conditions and higher levels of acceleration were observed at low velocities. These factors are thought to be among the main reasons for the gap between 10-15 mode FE and actual FE values.

Figure 3 depicts the simulated results of the 10-15 mode FC and the actual FC for a passenger gasoline engine vehicle (GV) with a 2,000 cc displacement. The results were calculated under vehicle driving simulation model (Kudoh et al., 2001). At a similar average velocity (as shown in Figure 2), the actual FC was about 13% lower than predicted by the 10-15 mode test. In addition, the actual FC of a vehicle clearly varied according to where it was driven, because the main cause of changes in average velocity is the stop-and-go traffic pattern that occurs frequently in urban areas.

As pointed out by Farrington & Rugh (2000) and Nishio et al. (2008), another important factor that should affect the FC/FE gap is the use of air conditioning, because the air conditioning system is turned off in most test cycles on the chassis dynamometer, including in the Japanese 10-15 mode.




(a) Driving pattern

(b) Relationship between velocity and acceleration

**Figure 1.** Japanese 10-15 mode driving schedule.

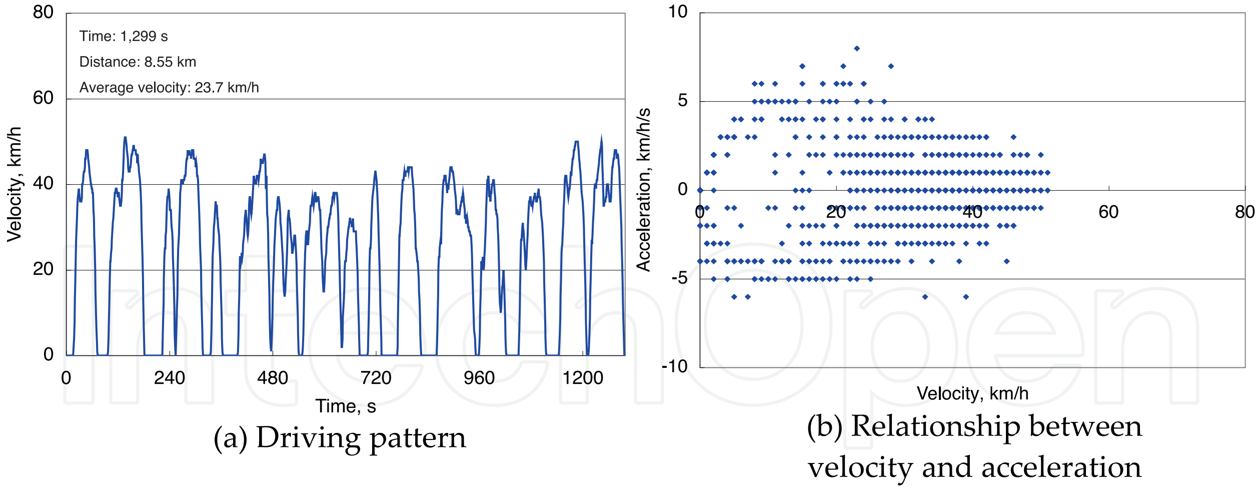



**Figure 2.** An example of actual vehicle travel activity (TMGBE, 1996).

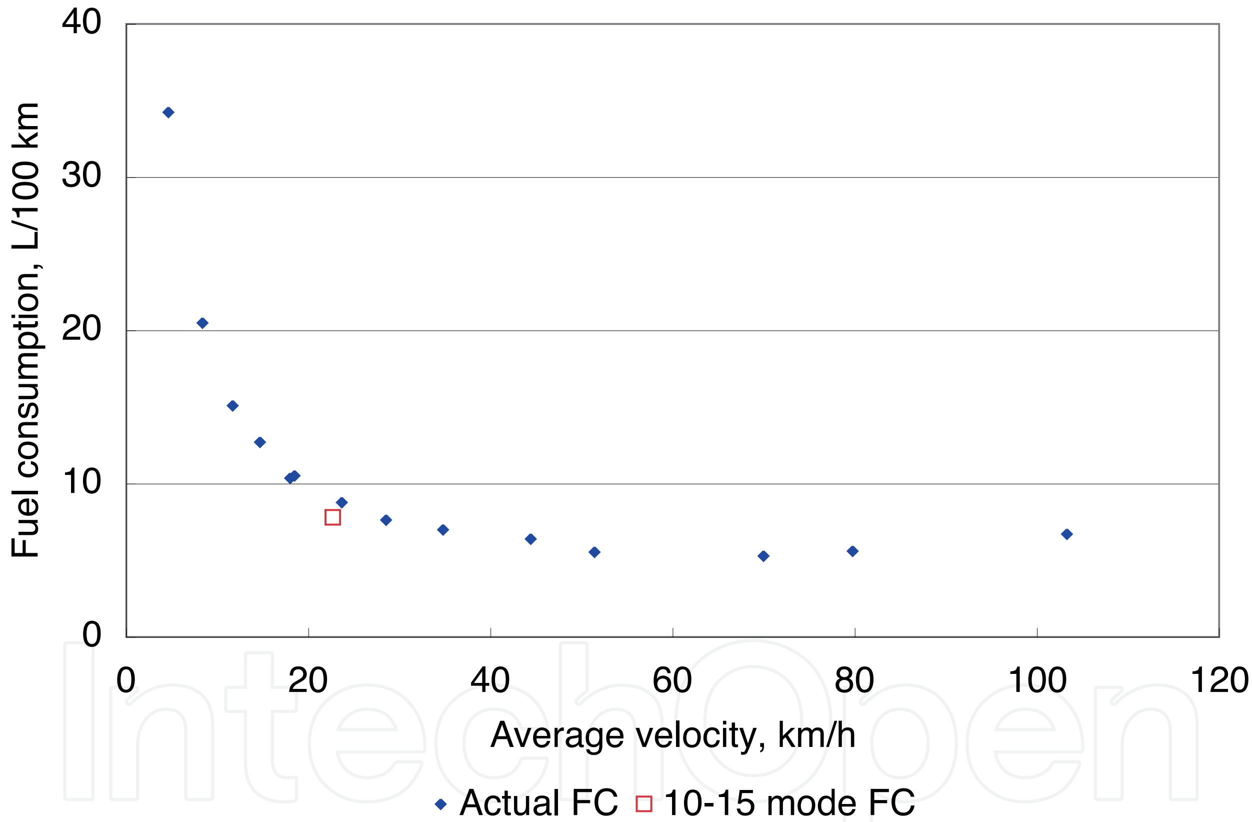



**Figure 3.** Simulated FC of a passenger vehicle with a 2,000cc gasoline engine.

## 3. Outline of the actual FC database

Figure 4 outlines the actual FC database that the author's group has been developing based upon the catalogue data of passenger vehicles sold in Japanese market and the voluntarily reported FC log data of vehicle users.

To obtain the passenger vehicle specifications for cars sold in Japan before March 2005, vehicle catalogues for each vehicle name, model year, and model grade were downloaded from an available website on the internet. The vehicle specification database contained information on 35,177 vehicles.

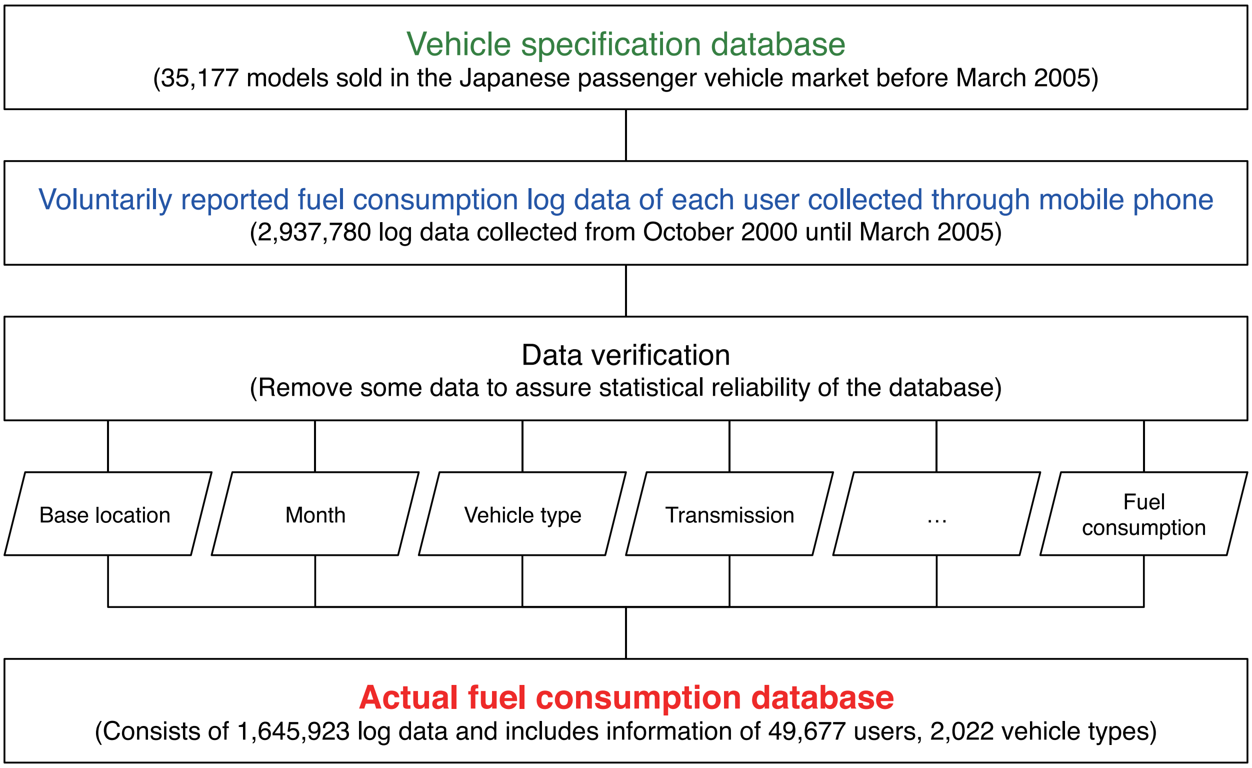



**Figure 4.** Outline of the actual FC database.

The actual FC database was developed by using voluntarily reported FC data from vehicle users and the vehicle specification database. The FC data collection system is called *e-nenpi* (which stands for "electronic FE" in Japanese[1]); this is an online service for internet-connected mobile phone users[2] provided by IID, Inc. The system manages information for vehicle owners, including FC performance and recommended routine maintenance. Users of the service register and provide the following information: (1) zip code of residence, (2) vehicle type[3], (3) type of engine air intake (turbocharged/supercharged or normal), (4) transmission type (manual or automatic[4]), and (5) type of fuel used (unleaded gasoline, premium unleaded gasoline, diesel, or liquefied petroleum gas). Through their mobile phone, the user then enters the amount of fuel put into the vehicle's tank and the odometer reading at the time of fuelling, and the user's FC data are stored on a server.

The items required for service registration were linked with the vehicle specification database and supplemented with other items such that the following 17 attributes were

[1] More information is available at: http://e-nenpi.com (in Japanese).

[2] Although the service was originally provided only for internet-connected mobile phone users, the provider currently offers the service for personal computers as well.

[3] Vehicle type is a code prepared by vehicle makers and approved by the government for vehicles sold and used in Japan to identify each vehicle.

[4] Although the FC may differ depending on the type of automatic transmission, they are grouped together within the database owing to data restrictions.

included in the actual FC database for each user: (1) user ID, (2) base location of where the vehicle was used[5], (3) month and year when the vehicle was fuelled, (4) vehicle maker, (5) vehicle name, (6) vehicle type, (7) vehicle class (light passenger vehicle[6] (LP) or passenger vehicle (P)), (8) type of powertrain (gasoline vehicle (GV), diesel vehicle (DV) or hybrid vehicle (HV)), (9) type of air intake, (10) transmission type, (11) type of drive system (2WD or 4WD), (12) type of fuel injection engine (direct injection or not), (13) whether a variable valve timing system was used, (14) fuel tank capacity, (15) engine displacement, (16) vehicle kerb weight, and (17) 10-15 mode FE.

Although technological specifications may vary within the same vehicle type by grade or model year owing to differences in equipment or improvement in vehicle technologies, the model year of the vehicle owned by each user could not be specified from the log data. Hence, the following values obtained from the vehicle specification database were used in the technological specifications of a vehicle type in the actual FC database: (1) maximum fuel tank capacity, (2) simple average of minimum and maximum vehicle weight, and (3) simple average of minimum and maximum 10-15 mode FE.

A total of 2,937,780 FC log data points was collected over the 54-month study period (from October 2000 through March 2005). Data were excluded under the following conditions to assure the statistical reliability of the database:

a. when the base location of vehicle use could not be specified (21,736 entries);
b. when users specified a vehicle type that was not included in the vehicle specification database (611,357 entries); and
c. when the fuel fill-up rate ($\gamma$) was less than 60% or more than 100% (536,620 entries). The rate was calculated as $\gamma = f / C$, where $f$ [L] is the amount of fuel put into the tank and $C$ [L] is the fuel tank capacity.

$FE_{u,v}$ [km/L], the FE of user $u$ who owns vehicle type $v$, was calculated by Equation 1, where $d_{u,v,i}$ [km] is driving distance from the last fuelling of the $i$ th data point, $f_{u,v,i}$ [L] is the amount of fuel obtained for data point $i$, and $n_{i \in u,v}$ is the number of log data entries.

$$FE_{u,v} = \sum\nolimits_{i \in u,v} (d_{u,v,i} / f_{u,v,i}) / n_{i \in u,v} \tag{1}$$

$FE_v$ [km/L], the FE of vehicle type $v$, was calculated by using Equation 2, where $n_{u \in v}$ is the number of users who own $v$.

$$FE_v = \sum\nolimits_{u \in v} FE_{u,v} / n_{u \in v} \tag{2}$$

Data entries were eliminated from further analysis if they met any of the following conditions:

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[5] This was determined from the zip code provided by the registered user.

[6] A light passenger vehicle is equivalent to, or smaller than, the EU's A-segment. Its physical size and engine power are regulated as follows: maximum length, 3.39 [m]; maximum width, 1.48 [m]; maximum height, 2 [m]; maximum engine displacement, 660 [cc]; and maximum engine power, 64 [hp].

a. when $FE_{i \in u,v}$ was determined to be a statistical outlier by the Grubbs' test at a critical level of 5% (57,118 entries);
b. when $n_{i \in u,v}$ is less than 5 (10,773 entries);
c. when the variance of $FE_{u \in v}$ is greater than 10 [(km/L)$^2$] (4,789 entries);
d. when $FE_{u \in v}$ was determined to be a statistical outlier by the Grubbs' test at a critical level of 5% (10,414 entries); and
e. when $n_{u \in v}$ is less than 3 (40,050 entries).

After all of the eliminations, 1,645,923 log data points, including pieces of information from 49,677 users and 2,022 vehicle types, were used to develop the actual FC database. A summary of the number of data points, users, and vehicle types is given in Table 1.

| Vehicle type | | Number of log data points | Number of users | Number of vehicle types |
|---|---|---|---|---|
| Light passenger gasoline vehicle (LP-GV) | < 702 kg | 23,563 | 848 | 57 |
| | 703 – 827 kg | 70,745 | 2,189 | 112 |
| | 828 – 1,015 kg | 55,655 | 1,654 | 93 |
| | 1,016 – 1,265 kg | 1,779 | 43 | 3 |
| | Total | 151,742 | 4,734 (0.035%[1]) | 265 (54.6%[2]) |
| Passenger diesel vehicle (P-DV) | 1,016 – 1,265 kg | 91 | 4 | 1 |
| | 1,266 – 1,515 kg | 496 | 19 | 5 |
| | 1,516 – 1,765 kg | 8,040 | 236 | 27 |
| | 1,766 – 2,015 kg | 28,021 | 809 | 57 |
| | 2,016 – 2,265 kg | 18,159 | 477 | 22 |
| | 2,266 kg + | 188 | 7 | 1 |
| | Total | 54,995 | 1,552 (0.061%[1]) | 113 (21.4%[2]) |
| Passenger gasoline vehicle (P-GV) | < 702 kg | 1,179 | 48 | 4 |
| | 703 – 827 kg | 10,626 | 380 | 20 |
| | 828 – 1,015 kg | 120,105 | 4,005 | 169 |
| | 1,016 – 1,265 kg | 346,834 | 10,968 | 481 |
| | 1,266 – 1,515 kg | 600,790 | 17,468 | 567 |
| | 1,516 – 1,765 kg | 281,517 | 8150 | 285 |
| | 1,766 – 2,015 kg | 51,055 | 1543 | 84 |
| | 2,016 – 2,265 kg | 18,398 | 526 | 24 |
| | 2,266 kg + | 3298 | 87 | 2 |
| | Total | 143,3802 | 43,175 (0.108%[1]) | 1,636 (41.3%[2]) |
| Passenger (gasoline) hybrid vehicle (P-HV) | 703 – 827 kg | 66 | 4 | 1 |
| | 828 – 1,015 kg | 379 | 12 | 1 |
| | 1,016 – 1,265 kg | 2,455 | 86 | 3 |

| Vehicle type | | Number of log data points | Number of users | Number of vehicle types |
|---|---|---|---|---|
| | 1,266 – 1,515 kg | 671 | 43 | 1 |
| | 1,766 – 2,015 kg | 1,447 | 51 | 1 |
| | 2,016 – 2,265 kg | 366 | 20 | 1 |
| | Total | 5,384 | 216 (0.111%[1]) | 8 (57.1%[2]) |
| Total | | 1,645,923 | 49,677 (0.089%[1]) | 2,022 (40.5%[2]) |

**Table 1.** Data size categories of the actual FC database. The vehicle weight class follows the Japanese inertia weight classes for passenger vehicles. [1] Sampling rate relative to the number of vehicles owned as of March 2005. [2] Sampling rate relative to the number of vehicle types included in the vehicle specification database.

Although Equations 1 and 2 assume that users fill their tanks to the same (full) level at every refuelling, there may be users who do not do so. The *e-nenpi* system recommends that registered users fill up the vehicle tank, and a confirmation message to check whether they have filled up the tank is shown when they input their fuel log through the mobile phone. The second and subsequent log data entries were saved in the server only after a user had confirmed filling up more than twice. In addition, some data were eliminated if they did not satisfy criterion c; the average of fuel fill-up rate of the remaining log data was 76.8% (standard deviation = 8.82%). Users should refuel before the tank was completely empty, indicating that most of the user data included in the actual FC database were acquired as the users filled up at petrol stations, so the fill level of the vehicles was expected to be almost the same every time.

## 4. Vehicle specifications and actual FC/FE

In the Japanese passenger vehicle market, 12 HV types had been launched as of March 2005; 8 were included in the actual FC database. It is assumed that the FC/FE performance of these vehicles would vary with differences in the powertrain configuration (e.g., series hybrid, parallel hybrid, or power-split hybrid) or degree of hybridisation (such as full hybrid, power-assist hybrid, mild hybrid, or plug-in hybrid). However, because of the difficulties involved in including all of these factors with a high level of statistical reliability, the passenger HV types were combined in this study.

### 4.1. Japanese 10-15 mode and actual FE

Figure 5 depicts the relationship between the Japanese 10-15 mode FE and actual FE. $FE_{v,actual}$ [km/L], the actual FE of vehicle type $v$, was calculated from Equation 3 (USEPA 2010), where $d_{v,i}$ and $f_{v,i}$ are driving distance [km] and amount of fuel [L] at $i$ th log data point of vehicle $v$.

$$FE_{v,actual} = \sum_{i \in v} d_{v,i} / \sum_{i \in v} f_{v,i} \tag{3}$$

Table 2 shows the results of a linear regression analysis and the 95% confidential interval (95 CI) described by Equation 4, where $FE_{v,10\text{-}15}$ [km/L] is the 10-15 mode FE of vehicle $v$ .

$$FE_{v,actual} = a \cdot FE_{v,10-15} \quad (4)$$

If a plotted point was on the diagonal line shown in Figure 5, the actual FE of the vehicle was exactly the same as 10-15 mode FE. As can be seen in the figure, the gap between 10-15 mode FE and actual FE increased as the 10-15 mode FE increased.

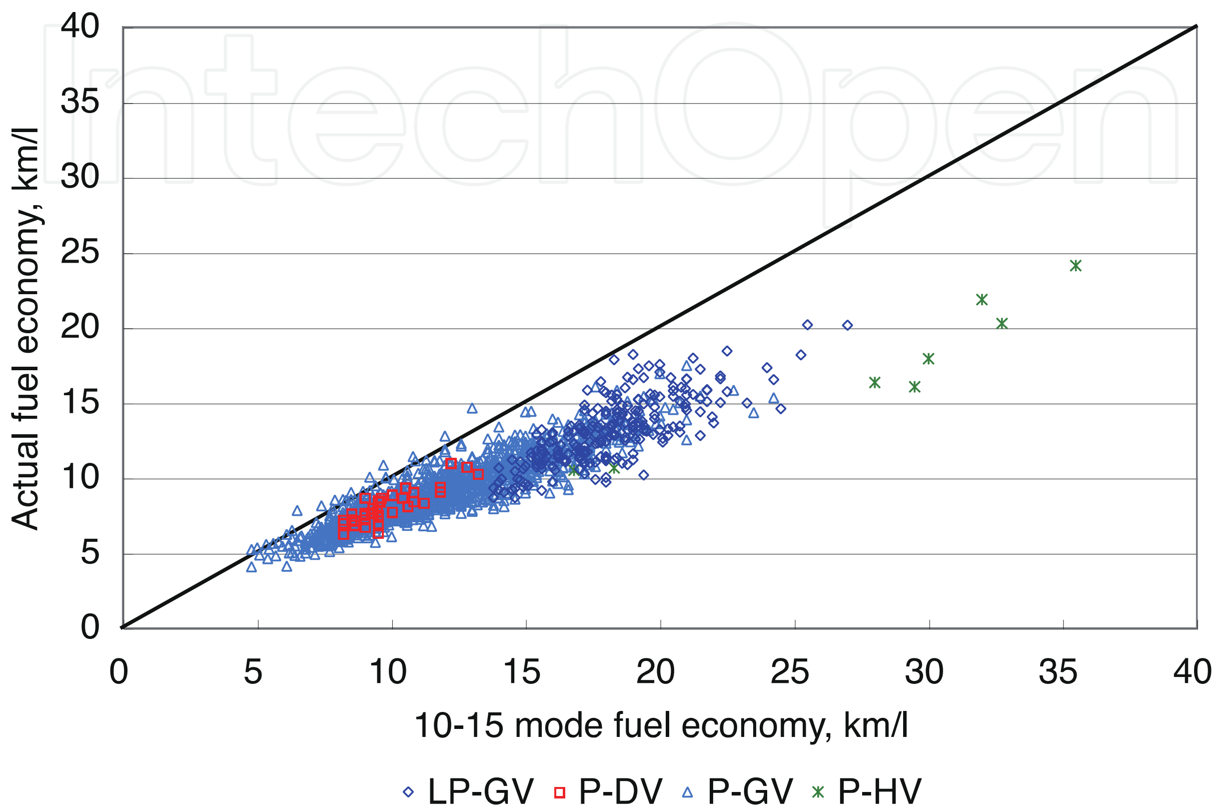


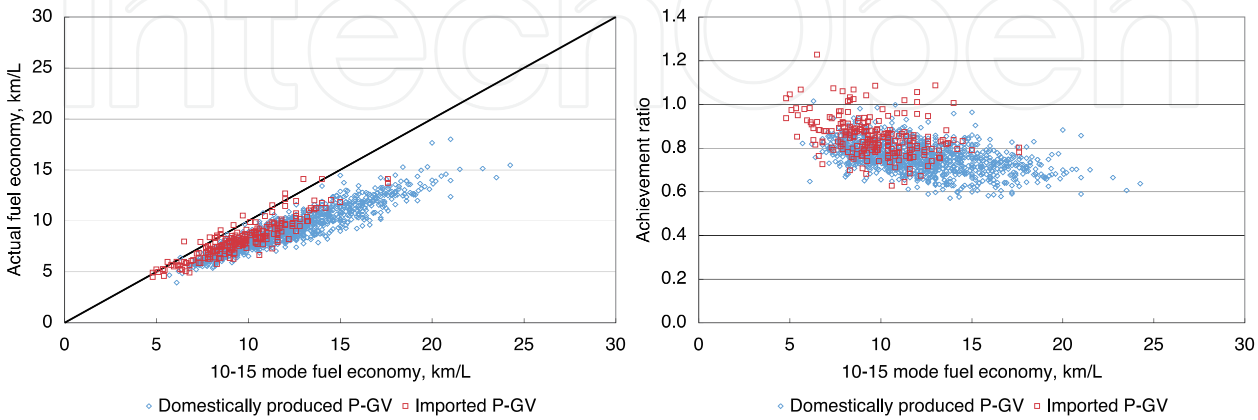

**Figure 5.** 10-15 mode FE and actual FE.

| | LP-GV | P-DV | P-GV | P-HV |
|---|---|---|---|---|
| *n* | 240 | 36 | 1,352 | 8 |
| $R^2$ | 0.989 | 0.995 | 0.989 | 0.994 |
| *a* (95 CI) | 0.725 (0.715–0.735) | 0.823 (0.803–0.844) | 0.760 (0.756–0.765) | 0.622 (0.579–0.666) |
| *t* | 144.3 | 82.6 | 346.1 | 34.0 |

**Table 2.** Estimates of parameters by Equation 4. *t* is the t statistics.

25 P-GVs had an actual FE that was higher than the corresponding 10-15 mode FE. (These are above the line in Figure 5.) Figure 6 shows the achievement ratio of actual FE to 10-15 mode FE of domestically produced and imported P-GVs; 23 out of the 25 P-GVs with a ratio of greater than 1 were imported vehicles. These results indicate that the achievement ratio of actual FE to 10-15 mode FE may be higher for imported vehicles than for domestically produced vehicles. The results of a two-tailed Welch test confirmed that the mean

achievement ratios of domestically produced passenger vehicles ($x$) were significantly lower than those of imported passenger vehicles ($y$) (mean of $x = 0.758$, variance of $x = 0.00445$, mean of $y = 0.854$, variance of $y = 0.00810$, $T = 15.1$, degree of freedom = $268$; $p < 0.05$). One possible explanation is that the drivetrains or transmissions of imported vehicles are not optimised for Japanese road conditions and their 10-15 mode FEs tend to be lower than their counterpart domestically produced P-GVs.




(a) 10-15 mode FE and actual FE

(b) Achievement ratio of actual FE to 10-15 mode FE

**Figure 6.** Comparison of domestically produced P-GVs and imported P-GVs.

## 4.2. Vehicle weight and actual FC

Weight-saving technologies in passenger vehicles will play an important role in improving FC, along with improvements in engine and drivetrain efficiency. Figure 7 depicts the relationship between vehicle weight and actual FC. Here, $FC_{v,actual}$ [L/100 km], the actual FC of vehicle type $v$, is calculated by Equation 5.

$$FC_{v,actual} = 100 \cdot \sum_{i \in v} f_{v,i} \,/\, \sum_{i \in v} d_{v,i} \tag{5}$$

Two FC standards are shown in Figure 7: the Japanese 2010 standard for GVs and the 2005 standard for DVs. Points plotted above the two lines represent vehicles that do not achieve the FC standards in the real world. Although most brand-new passenger vehicles were announced to have achieved the FC standard by 2005, Figure 7 reveals that only some P-DVs and all the P-HVs achieved the Japanese FC standard in the real world at that time.

Since $FC_{v,actual}$ can be thought to be proportional to vehicle weight $w$ [kg], a linear regression analysis was conducted by using Equation 6 (Table 3).

$$FC_{v,actual} = b \cdot w + c \tag{6}$$

The analysis showed that it is difficult to explain the FC of LP-GVs and P-DVs only by vehicle weight. Sales of brand-new LP-GVs, which are restricted in terms of vehicle size and engine displacement, are rapidly expanding in Japan, and Japanese vehicle makers provide a variety of vehicle types (e.g., hatchbacks and wagons) within the regulatory standard. To compensate for the increase in vehicle weight incurred by equipment installed to meet consumer needs or to satisfy safety standards, many LP-GVs use turbochargers. Including only LP-GVs that were introduced to the market after 1998 (when the LP vehicle standards were changed to meet new crash safety standards), the engine displacement of LP-GVs were from 657 – 660 [cc] but their average vehicle weight was 842 [kg] with a wide variation from 550 and 1,060 kg. As a result, the FC differs owing to differences in running resistance (attributed mainly to differences in vehicle shape), transmission type, drive system, and turbocharging, which result in the low $R^2$ value (0.471).

| | LP-GV | | P-DV | | P-GV | | P-HV | |
|---|---|---|---|---|---|---|---|---|
| $n$ | 265 | | 113 | | 1,636 | | 8 | |
| $R^2$ | 0.471 | | 0.336 | | 0.700 | | 0.925 | |
| | $b\times10^{-3}$ | $c$ | $b\times10^{-3}$ | $c$ | $b\times10^{-3}$ | $c$ | $b\times10^{-3}$ | $c$ |
| $B$ (95 CI) | 9.09 (7.92–10.3) | 0.493 (-0.445 –1.43) | 5.10 (3.75 –6.45) | 2.95 (0.433 –5.47) | 8.45 (8.18 –8.72) | 0.446 (0.0792 –0.812) | 4.64 (3.32 –5.96) | 0.238 (-1.57 –2.04) |
| $t$ | 15.3 | 1.03 | 7.49 | 2.32 | 61.8 | 2.39 | 8.60 | 0.322 |

**Table 3.** Estimates of parameters by Equation 6. $n$ is sample number, $B$ is partial regression coefficient and $t$ is t statistics, respectively.

Of the 113 P-DVs plotted in Figure 7, 25 are 4WD, 92 have AT/CVT transmission, 108 are turbocharged, and 11 have a direct injection engine. The vehicle weight range of 1,705—2,165 [kg] is small compared with that of P-GVs (715—2,380 [kg]). The low $R^2$ value (0.336) for P-DVs indicate that it is difficult to explain actual FC only with vehicle weight, for the actual FC of a vehicle varies by the combinations of various vehicle specifications.

### 4.3. Effect of vehicle technologies on actual FC of gasoline-fuelled passenger vehicles

A multiple regression analysis was conducted to evaluate the effect of vehicle technologies on the actual FC of gasoline-fuelled passenger vehicles (P-GVs and P-HVs). A P-GV with a manual transmission and 2WD was set as the baseline. The regression equation can be described as Equation 7:

$$\begin{aligned} FC_{v,actual} &= d_0 + d_1 w + d_2 D_{HV} + d_d D_{AT/CVT} \\ &\quad + d_4 D_{TC} + d_5 D_{4WD} + d_6 D_{DI} + d_7 D_{VVT} \end{aligned} \quad (7)$$

where $w$ is vehicle weight [kg] and $D_{HV}$, $D_{AT/CVT}$, $D_{TC}$, $D_{4WD}$, $D_{DI}$, and $D_{VVT}$ are the dummy variables for P-HV, transmission (AT/CVT), turbocharging (TC), 4WD, direct injection (DI), and variable valve timing (VVT), respectively. The parameter estimates are summarized in Table 4.

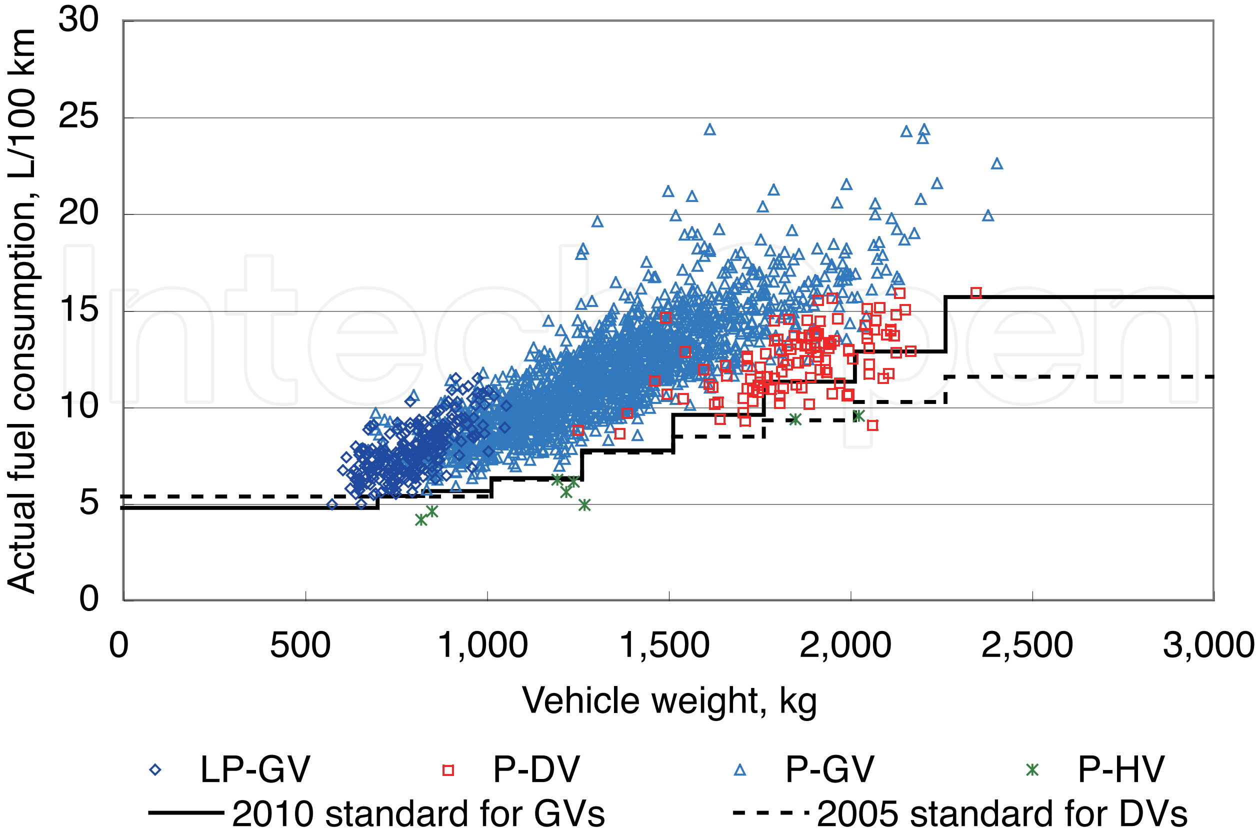



**Figure 7.** Vehicle weight and actual FC

Using the estimates shown in Table 4 and Equation 7, it is confirmed that the use of direct injection and variable valve timing led to a decrease in actual FC, whereas the use of an automatic transmission and turbocharging resulted in an increase in actual FC. Although the partial regression coefficients of HV and 4WD are negative, adding hybrid technology and 4WD to a baseline P-GV increased vehicle weight. Hence, to evaluate the effect of hybridisation and 4WD, the balance between vehicle weight increase and the coefficients of the dummy variables given in Table 4 should be considered.

Among the 8 HV models included in the actual FC database, 3 models also had equivalent GVs within the same vehicle name, 3 had engines that were variants of the GV models, and 2 were dedicated HV models. Therefore, counterpart GV models could be defined for 6 of the 8 HV models. Although the vehicle weight of HVs depends upon various vehicle specifications, the weight increase of these 6 HVs from their counterpart GVs ranged from 40 to 195 [kg]. Equation 7 and Table 4 were then used to estimate a 0.336—1.64 [L/100km] increase in actual FC from hybridisation. Because the actual FC improvement effect evaluated from the partial regression coefficient of HV prevailed in this estimate, however, it is estimated that hybridisation contributed to an actual FC improvement (-4.44 to -3.14 [L/100km]) from the baseline P-GV.

Of the 1,615 samples analysed in this section, 370 had the same vehicle name and model year for both 2WD and 4WD models (other specifications, such as transmission type, turbocharging, and direct injection, were the same). The use of 4WD increased weight by

83.1 [kg] on average (standard deviation = 38.8 [kg]). The partial regression coefficients $d_1$ and $d_5$ shown in Table 4 indicate that a weight increase of 83.1 kg would result in an actual FC increase of 0.329 [L/100km].

| $n$ | 1,615 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $R^2$ | 0.799 | | | | | | | |
| | $d_0$ | $d_1 \times 10^{-3}$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $d_6$ | $d_7$ |
| $B$ (95 CI) | 0.487 (0.206 – 0.768) | 8.39 (8.16 – 8.63) | -4.77 (-5.71 – -3.83) | 0.532 (0.379 – 0.685) | 0.952 (0.777 – 1.13) | -0.368 (-0.520 – -0.217) | -1.01 (-1.41 – -0.699) | -1.02 (-1.18 – -0.869) |
| $t$ | 3.40 | 70.9 | -9.98 | 6.83 | 10.6 | -4.77 | -5.81 | -13.0 |

**Table 4.** Estimates of parameters by Equation 7. $n$ is sample number, $B$ is partial regression coefficient and $t$ is t statistics, respectively.

## 5. Annual differences in mean actual FC of gasoline-fuelled passenger vehicles

Annual (fiscal year, FY) changes in vehicle weight and actual FC for gasoline-fuelled passenger vehicles from FY 2001 to 2004 are analysed. Table 5 presents the descriptive statistics of vehicle weight for gasoline-fuelled passenger vehicles (P-GVs and P-HVs) that were used to conduct a one-factor analysis of variance. No significant difference was observed for mean vehicle weight of P-HVs ($F$ = 0.252, $p$ = 0.859), but a significant difference was found for P-GVs ($F$ = 2.71, $p$ = 0.044). Therefore, a post-hoc multiple comparison by Sheffé's test on vehicle weight of P-GVs was conducted, but no significant differences were observed.

Similarly, the mean differences of actual FC are tested. As shown in Section 4.2, actual FC is presented as proportional to vehicle weight; therefore, an analysis of covariance was carried out to adjust for the effect of vehicle weight in actual FC. Mean actual FC of P-GVs decreased significantly from FY2001 until FY2004 ($F$ = 19.7, $p$ = 0.000). Post-hoc multiple comparisons with the Sidak adjustment showed that the mean actual FC values adjusted for vehicle weight were significantly different, except between FY2003 and FY2004 (Table 6). No significant differences were observed for P-HVs ($F$ = 0.299, $p$ = 0.826).

The results indicate that the actual FC of P-GVs included in the actual FC database steadily improved, most likely as a result of an increase in the number of vehicles equipped with FC-improving technologies and not because of weight reductions. The lack of significant changes for P-HVs can be attributed to the fact that only small numbers of new-type P-HVs had entered the Japanese passenger vehicle fleet at the time of the study and also to a lack of drastic improvements in the P-HVs produced during this period.

| FY | P-GV | | | P-HV | | |
|---|---|---|---|---|---|---|
| | $n$ | $\mu$ | $\sigma$ | $n$ | $\mu$ | $\sigma$ |
| 2001 | 970 | 1,330.92 | 268.04 | 5 | 1,196.00 | 415.73 |
| 2002 | 1,073 | 1,342.16 | 275.34 | 4 | 1,290.00 | 414.17 |
| 2003 | 1,091 | 1,353.79 | 272.29 | 7 | 1,378.57 | 410.15 |
| 2004 | 1,089 | 1,362.95 | 269.70 | 7 | 1,378.57 | 410.15 |
| All | 4,223 | 1,347.94 | 271.70 | 23 | 1,323.48 | 390.39 |

**Table 5.** Descriptive statistics of vehicle weight [kg]. $n$ is the number of vehicle types, $\mu$ is the population mean, and $\sigma$ is standard deviation.

| [L/100km] | FY2002 | FY2003 | FY2004 |
|---|---|---|---|
| FY2001 | 0.190* | 0.403* | 0.441* |
| FY2002 | | 0.213* | 0.251* |
| FY2003 | | | 0.038 |

**Table 6.** Results of post-hoc multiple comparisons using the Sidak adjustment for the mean actual FC of P-GVs. The value in each cell shows the differential in the population mean $\mu_r$ in rowwise group $r$ and $\mu_c$ in columnwise group $c$. For example, $\mu_{FY2001} - \mu_{FY2002} = 0.190$. Asterisk denotes significance at 5% level.

## 6. Validity of actual FC obtained from the actual FC database

To check the validity of the actual FC values calculated from the database, two cases from the database were compared with a third that was calculated from published statistics for gasoline-fuelled passenger vehicles (P-GVs and P-HVs):

Case A: The actual FC of gasoline-fuelled passenger vehicles was estimated for each FY directly from the database.

Case B: The actual FC of gasoline-fuelled passenger vehicles was estimated from the results of the regression analysis between vehicle weight and actual FC (Table 7, Equation 6) and the estimated number of vehicles owned, by vehicle weight (by 10 kg increments), for each FY.

Case C: The actual FC of gasoline-fuelled passenger vehicles was estimated from national statistics (MLIT, 2003–2005).

For Case B, the number of vehicles owned by vehicle weight was estimated from the vehicle specification database and various published statistics (AIRIA1, 2003–2005; AIRIA2, 2003–2005; AIRIA3, 2003–2005). Figure 8 shows the ownership rate (OR) relative to the total number of vehicles owned, by Japanese inertia weight class, for passenger vehicles from FY2002 (March 2003) to FY2004 (March 2005). The sampling rate (SR) — the number of vehicles actually included in the estimates of Case A as a ratio of the total number of vehicles owned — is also shown in the figure. The vehicle weight distribution of the database (SR) does not reflect the real-world distribution (OR); OR has a normal distribution, whereas SR is higher for both light (< 702 [kg]) and heavy (1,766+ [kg]) vehicles. Therefore, actual FC values compiled directly from the database in Case A might have been biased as a result of the vehicle weight distribution.

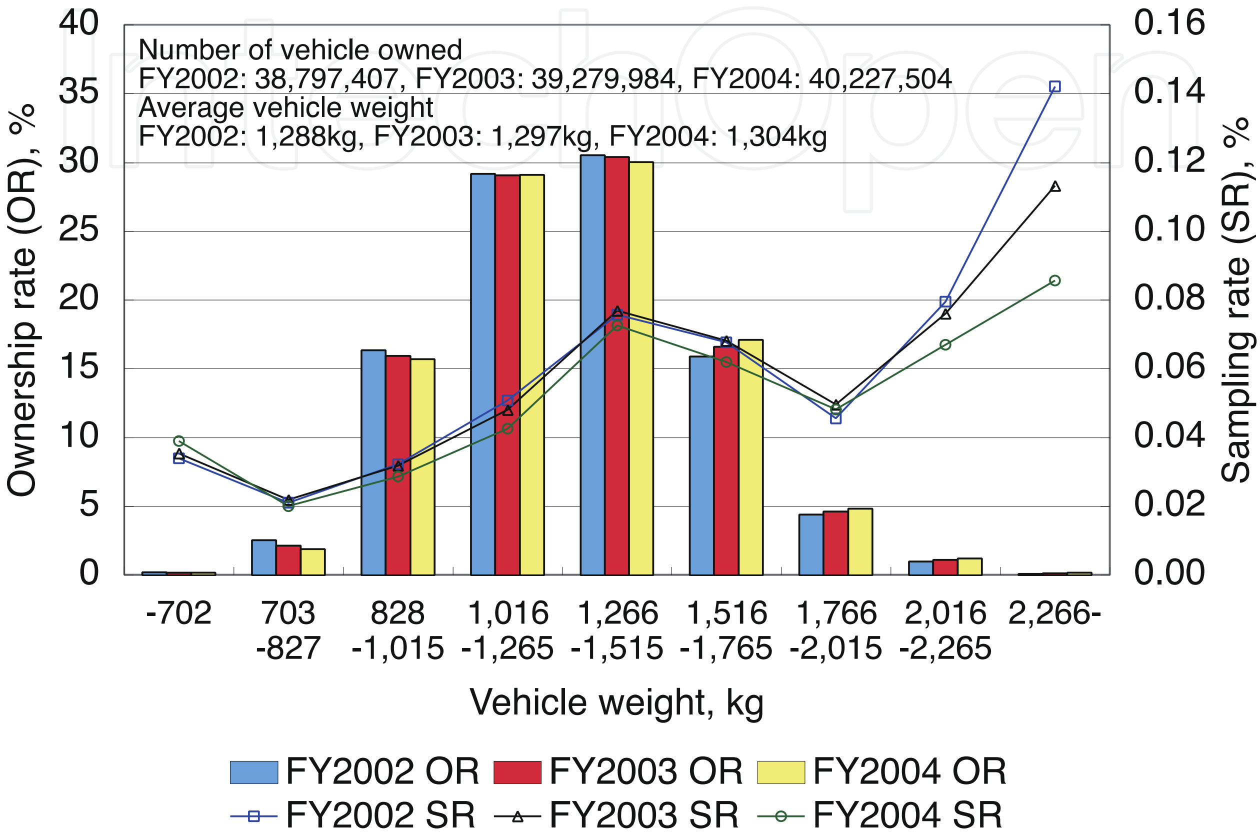



**Figure 8.** Ownership rates of gasoline-fuelled passenger vehicles and sampling rates of vehicles included in the database.

As described in Section 4, the mean actual FC adjusted by vehicle weight improved each year in the study period. Therefore, Case B was designed to reflect improvements in actual FC adjusted for the vehicle weight bias that might have been included in the database (Case A). Because no significant improvement in actual FC was observed for P-HVs from FY2002 to FY2004, the results of the regression analysis shown in Table 3 were used for P-HVs; the results from Table 7 were used for P-GVs.

Table 8 shows the estimates of actual FC of gasoline-fuelled passenger vehicles for the three cases from FY2002 to FY2004. The actual FC steadily improved from FY2002 to FY2004 in Cases A and C, but the actual FC did not improve from FY2003 and FY2004 in Case B, similar to the results in the same time period shown in Table 6. Although there are small differences in each FY, the estimates of actual FC of gasoline-fuelled passenger vehicles in Cases A and B were within 4% of the Case C estimates in all instances. Therefore, the actual FC values derived from the database appear to be compatible with the estimates from published statistics.

| | FY2002 | | FY2003 | | FY2004 | |
|---|---|---|---|---|---|---|
| *n* | 1,073 | | 1,091 | | 1,089 | |
| $R^2$ | 0.729 | | 0.704 | | 0.684 | |
| | $b \times 10^{-3}$ | *c* | $b \times 10^{-3}$ | *c* | $b \times 10^{-3}$ | *c* |
| *B* (95 CI) | 8.57 (8.25 – 8.88) | 0.338 (-0.0910 – 0.767) | 8.38 (8.06 – 8.70) | 0.377 (0.0692 – 0.822) | 8.33 (7.99 – 8.67) | 0.408 (0.0599 – 0.876) |
| *t* | 53.7 | 1.55 | 50.9 | 1.66 | 48.5 | 1.71 |

**Table 7.** Estimates of parameters by Equation 4 for P-GVs for FY2002–2004. *n* is sample number, *B* is partial regression coefficient and *t* is t statistics, respectively.

| Case or comparison | FY2002 | FY2003 | FY2004 |
|---|---|---|---|
| Case A | 11.81 | 11.62 | 11.59 |
| Case B (95CI) | 11.36 (11.24 – 11.48) | 11.23 (11.10 – 11.36) | 11.24 (11.11 – 11.37) |
| Case C | 11.66 | 11.49 | 11.13 |
| Case A / Case C | 1.01 | 1.01 | 1.04 |
| Case B / Case C (95 CI) | 0.974 (0.964 – 0.984) | 0.977 (0.966 – 0.988) | 1.01 (0.998 – 1.02) |

**Table 8.** Comparison of actual FC [L/100km] of gasoline-fuelled passenger vehicles for Cases A–C.

## 7. Conclusion

In order to quantify the relationship between vehicle specifications and actual FC with statistical reliability, an actual FC database was developed by using vehicle specification data and voluntarily reported data collected from an internet-connected mobile phone system throughout Japan. The database was used to conduct statistical analyses to evaluate the effects of various vehicle specifications on the FC/FE of passenger vehicles. The actual FC adjusted by vehicle weight was shown to have significantly improved from FY2001 to FY 2004. Moreover, estimates of the actual FC of gasoline-fuelled passenger vehicles obtained from the database were consistent with estimates calculated from national statistics.

With the revision of the Energy-Saving Law in July 2007, Japan changed from using the 10-15 mode to the JC08 mode (UNEP, 2012); the new 2015 FE standards for passenger vehicles are based on the Top Runners Approach provided in the JC08 mode. Japanese vehicle makers have already started to sell new passenger vehicles that have achieved the 2015 FE standard, so the effects of equipping vehicles with various types of new and more fuel efficient technologies may influence the actual FC of these vehicles as well. The author's group plans to extend the data collection period presented in this paper and to update the actual FC database to reflect state-of-the-art vehicle technologies in the real world.

Finally, the World Forum for Harmonization of Vehicle Regulations, which is a working party (WP.29) of the United Nations Economic Commission for Europe, has decided to set up an informal group under its Working Party on Pollution and Energy to develop a worldwide harmonized light duty test cycle (the Worldwide Harmonized Light Duty Vehicle Test Procedures, WLTP) by 2013. This cycle will represent typical driving conditions around the world (UNECE, 2012). Because the actual FC/FE of vehicles might show different trends if the WLTP is adopted and applied to meet new FC/FE standards, the movement towards the endorsement of the WLTP could influence future studies as well.

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