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# Real-World Fuel Consumption Performance of Hybrid Vehicles in Japan

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**Summary**

In order to investigate the real-world fuel consumption of vehicles on Japanese road, the author's group has been putting focus upon the voluntary reported fuel consumption log data of the users collected through internet from all over Japan and establishing a real-world fuel economy / consumption database. Using the latest database which includes pieces of information of 128,670 vehicle users and 2,815 vehicle types collected from October 2000 until September 2012, the real-world fuel consumption performance of hybrid vehicles and its relationship between vehicle specifications are evaluated in this study.

*Keywords: Energy consumption, Fuel, HEV, Gasoline engine*

## 1 Introduction

Currently the world's automotive energy is still strongly depending upon oil. Consequently, a large amount of carbon dioxide (CO2) emissions is generated in passenger automotive sector and are having a significant effect on the global environment. Among various measures from both automotive technology side and transport demand side to reduce energy consumption and CO2 emissions, improvement of fuel economy (FE, such as kilometers of travel per litres of fuel [km/L]) or fuel consumption (FC, such as litres of fuel per hundred kilometers of travel [L/100km]) of passenger vehicles are regarded as the most effective measure to lower the energy demand and CO2 emissions in this sector. In this context, many regions and countries around the world have implemented FE/FC or CO2 standards and even some of those, e.g. the United States, the European Union and Japan, are moving forward to tightening the standards.

The FE/FC and CO2 standards for type-approval measurements are performed on chassis dynamometers according to strictly determined test cycles, which simulate a variety of driving conditions at motorway and urban driving speeds typical in each country and region. Thanks to the developments on vehicle technologies, it is true that the type-approval FE/FC of vehicles has been improving from the past. However, it is quite well known that a gap exists between type approval and real-world FE/FC [1, 2]. It is because the real-world FE/FC strongly depends upon how and where we drive, congestions, weather and accordingly accessory use (especially air conditioning) or the maintenance condition of our vehicle; any single test cycle cannot simulate all the possible combinations of driver behaviour, traffic conditions, climate and car-care habits. Moreover, it is pointed out the divergence between type-approval and real-world fuel consumption is increasing in accordance with the type-approval fuel consumption improvement [3]. The energy roadmaps and CO2 reduction targets for passenger automotive sector in each region and country are mainly based upon the type-approval FE/FC and CO2 standards. However, it is not the figures by tests but those in the real world that counts. It is doubtful whether the reduction targets can be achieved without reflecting the precise real-world FE/FC or GHG emissions of vehicles. Providing the precise FE/FC in the real world can also inform the consumers of the expected fuel costs.

The smartphones and other internet-connected mobile devices have become wide spread in the world and a variety of mobile apps and services are provided. In order to investigate the real-world FE/FC performance of passenger vehicles in Japan, the author's group has been putting focus upon the mobile FE/FC management service for vehicle users from which voluntary reported FC log data of the users are collected through internet from all over Japan. By linking these FC log data and catalogue data of passenger vehicles sold in Japanese market, the author's group has been developing a real-world FC database. After reporting initial findings obtained from the real-world FE/FC information for 24 months from October 2000 to September 2002 [4], the database was updated by extending the data collection period to 54 months from October 2000 through March 2005, which consists of 1,645,923 pieces of log data from 49,677 passenger vehicle users on 2,002 models sold in Japan. Using the database, investigations for real-world FE/FC of passenger hybrid vehicles (HVs) and internal combustion engine vehicles are conducted and the divergence of between the Japanese 10-15 mode and real-world FC were identified [5, 6].

Owing to the changes in vehicle use situation and the advancement of measurement technology, 10-15 mode test cycle had been replaced by JC08 mode in 2011 and currently JC08 mode is used as the default test cycle for the Japanese type-approval test. In order to evaluate the latest passenger vehicle FE/FC observed in the real world, the author's group has updated the database by further extending the data collection period of the voluntary reported FC log data for 144 months from October 2000 until September 2012. The updated database is used in this study and statistical analyses will be conducted to evaluate the real-world FE/FC performance and its relationship between vehicle specifications including the Japanese JC08 mode FC.

## 2 Outline of the real-world FE/FC consumption database

Fig. 1 outlines the actual FE/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.

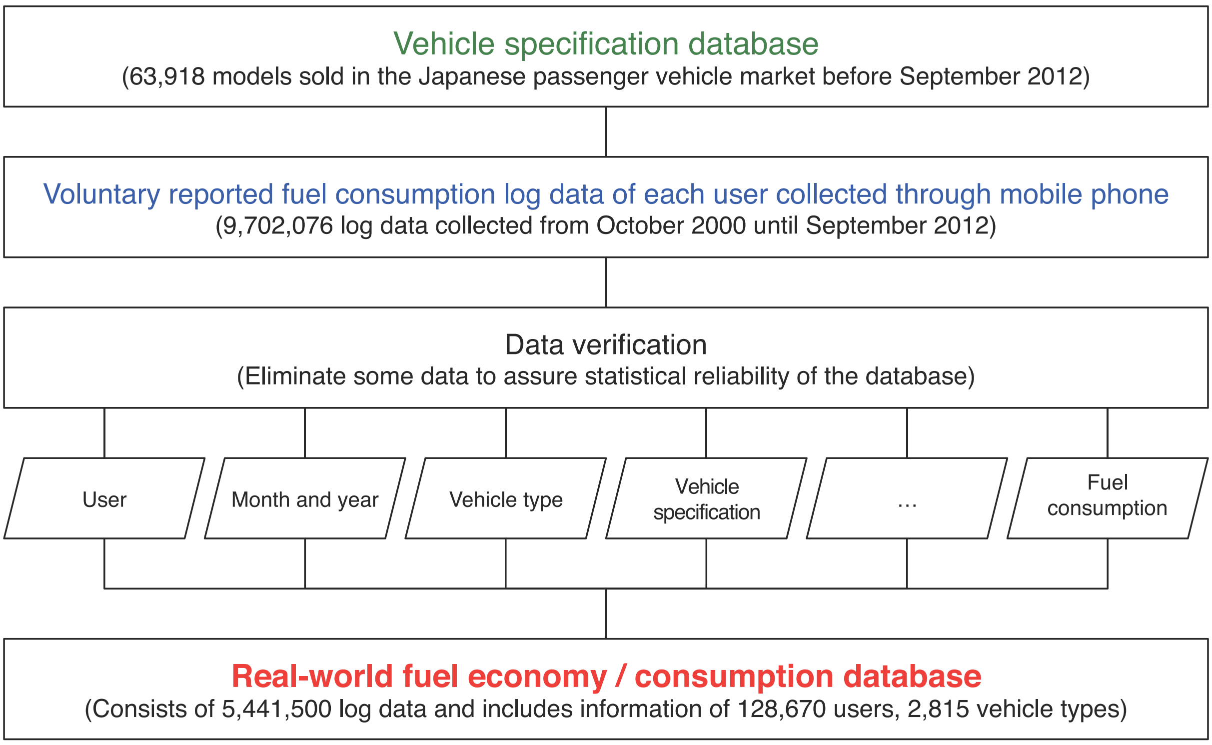


Figure 1: Outline of the real-world FE/FC consumption database

In order to obtain the passenger vehicle specifications for the cars sold in Japan before September 2012, 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 63,818 vehicles.

The real-world FE/FC database was developed by using voluntarily reported FE/FC data from vehicle users and the vehicle specification database. The FC data collection system is called "e-nenpi" (which stands for "electronic fuel economy" in Japanese. English details can be found at: http://www.iid.co.jp/english/service/enenpi.html) which is an online service provided by IID, Inc. to manage pieces of 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) type of engine air intake (turbocharged/supercharged or normal), (4) transmission type (manual (MT), automatic (AT) or continuously variable transmission (CVT)), and (5) type of fuel used (gasoline, diesel, liquefied petroleum gas, etc.). 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 included in the real-world FC database for each user: (1) user ID, (2) base location of where the vehicle was used , (3) month and year when the vehicle was fuelled, (4) vehicle maker, (5) vehicle name, (6) vehicle type, (7) vehicle class (light passenger vehicle or passenger vehicle), (8) type of powertrain (gasoline vehicle (GV), diesel vehicle (DV), hybrid vehicle (HV) or gasoline vehicle with Wankel rotary engine (GV-RT)), (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) Japanese type-approval FC.

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 real-world FC database: (1) maximum fuel tank capacity, (2) simple average of minimum and maximum vehicle weight, and (3) simple average of minimum and maximum type-approval FC.

A total of 9,702,076 FC log data points was collected over the 144-month study period (from October 2000 through September 2012). 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;

(b) when users specified a vehicle type that was not included in the vehicle specification database; and

(c) when the fuel fill-up rate ($\gamma$) was less than 60% or more than 100%. 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.

$$FE_{u,v} = \sum_{i \in u,v} (d_{u,v,i} / f_{u,v,i}) / n_{i \in u,v} \quad (1)$$

$FE_v$ [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 $v$.

$$FE_v = \sum_{u \in v} FE_{u,v} / n_{u \in v} \quad (2)$$

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

(d) when $FE_{i \in u,v}$ was determined to be a statistical outlier by the Grubbs' test at a critical level of 5%;

(e) when $n_{i \in u,v}$ is less than 5;

(f) when the variance of $FE_{u \in v}$ is greater than 10[(km/L)$^2$];

(g) when $FE_{u\in v}$ was determined to be a statistical outlier by the Grubbs' test at a critical level of 5%; and

(h) when $n_{u\in v}$ is less than 3.

After all of the eliminations, 5,441,500 log data points, including pieces of information from 128,670 users and 2,815 vehicle types, were used to develop the real-world FE/FC database. A summary of the number of data points, users, and vehicle types is given in Table 1.

Table 1: Data size of the real-world FE/FC database.

| Vehicle classification | Number of log data points | Number of users | Number of vehicle types |
|---|---|---|---|
| Japanese Kei passenger gasoline vehicle (K-GV) | 831,617 | 21,132 | 470 |
| Passenger gasoline vehicle (GV) | 4,344,783 | 100,743 | 2,191 |
| Passenger (gasoline) hybrid vehicle (HV) | 77,442 | 2,504 | 30 |
| Passenger diesel vehicle (DV) | 117,788 | 2,679 | 116 |
| Passenger gasoline vehicle with Wankel rotary engine (GV-RT) | 69,870 | 1,612 | 8 |
| Total | 5,441,500 | 128,670 | 2,815 |

# 3 Real-world FC of gasoline-fuelled passenger vehicles

In this study, special focuses will be put upon the real-world FC of passenger hybrid vehicles (HVs) and passenger gasoline vehicles (GVs) as their conventional counterpart.

## 3.1 Type-approval and real-world FC

Since 2011, the JC08 mode test cycle (Fig. 2) has been used for establishing the Japanese FE values. Fig. 3 shows the relationship between JC08 mode and real-world FC by vehicle type. Please note here that because the data collection period of the database is until September 2012, majority of the vehicles whose pieces of information are included in the database have the previous type-approval values (measured by Japanese 10-15 mode test cycle) so that only a limited number of data is plotted on Fig. 3.

Table 2 shows the results of a linear regression analysis and the 95% confidential interval (95CI) described by Equation (3), where $FC_{v,rw}$ [L/100km] and $FC_{v,JC08}$ [L/100km] are the real-world and JC08 mode FC of vehicle type $v$, respectively.

$$FC_{v,rw} = a \cdot FC_{v,JC08} \tag{3}$$

If the plot is on the line drawn upon Fig. 3, the real-world FC is exactly the same as JC08 mode FC. From Figure 3 and Table 2, it can be confirmed that FC performance of HV is absolutely better than that of GV but the divergence between type-approval and real-world FC tends to be greater than GV.

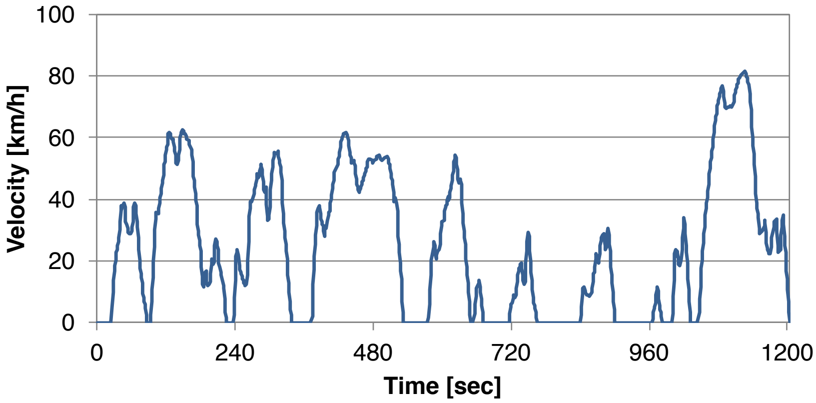


Figure 2: The Japanese JC08 mode test cycle

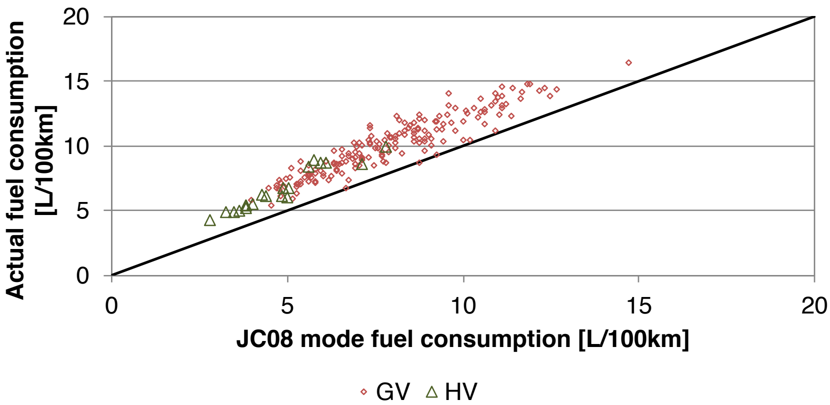


Figure 3: Relationship between type-approval and real-world FC

Table 2: Estimates of parameters by Equation (3)

| | GV | HV |
|---|---|---|
| Samples | 179 | 21 |
| Adjusted $R^2$ | 0.99 | 0.99 |
| $a$ | 1.259 | 1.373 |
| $t$ statistics | 143 | 59.4 |

## 3.2 Vehicle kerb weight and real-world FC

Fig. 4 shows the relationship between vehicle kerb weight and fuel consumption. The lines drawn upon the figures represent the 2020 target fuel consumption standard set in the Japanese Energy Saving Law (ESL) and thus the plots under the lines means that they have achieved the 2020 standard. Within the same vehicle weight class, HVs can be confirmed to demonstrate better real-world FC performance than GVs. It can also be said from Fig. 4 that only a couple of HV model can achieve the target on the road.

Using the plots of Fig. 4, a linear regression analysis using Equation (4) is conducted, whose results are shown in Table 3. Table 3 can be used to estimate the vehicle light-weighting effect upon the real-world FC of HVs and GVs.

$$FC_{v,rw} = b \cdot w_v + c \quad (4)$$

where $FC_{v,rw}$ [L/100km] and $w_v$ [kg] are the real-world FC and vehicle kerb weight of vehicle $v$.

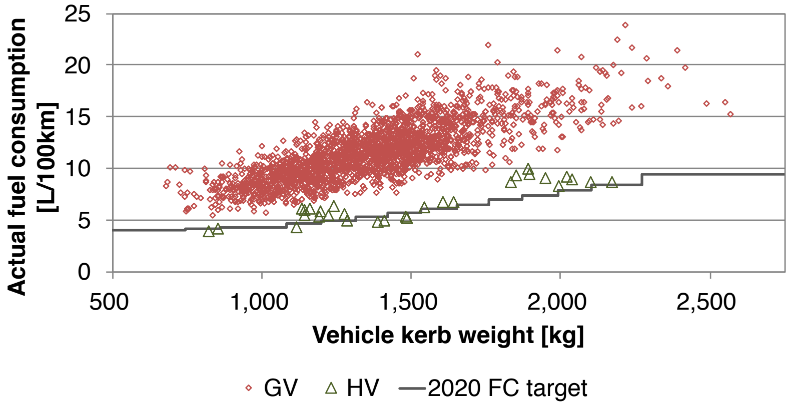


Figure 4: Relationship between vehicle kerb weight and real-world FC

Table 3: Estimates of parameters by Equation (4)

| | GV | HV |
|---|---|---|
| Samples | 2189 | 28 |
| Adjusted $R^2$ | 0.62 | 0.79 |
| $a$ | 0.00760 | 0.00424 |
| $t$ statistics of $a$ | 59.6 | 10.6 |
| $b$ | 1.21 | 0.330 |
| $t$ statistics of $b$ | 6.80 | 0.530 |

## 3.3 Comparison of HVs and their counterpart GVs

Real-world FC of HVs are compared to their counterpart GVs in this subsection. Table 4 shows the HVs included in the database and their counterpart GVs chosen for comparison in this study that are selected from the same vehicle manufacturers.

Table 4: Selection of HVs and their counterpart GVs

| HV type (engine disp.) | Specification (Vehicle kerb weight, transmission type, drive train type, model year) | Number of HV users / data points | Counterpart GV type (engine disp.) | Number of GV users / data points | Remarks |
|---|---|---|---|---|---|
| HV01 (995cc) | 820kg, MT, 2WD, 1999—2006 | 12 / 423 | GV01 (1,343cc) | 27 / 949 | #1 |
| HV02 (995cc) | 850kg, CVT, 2WD, 1999—2006 | 34 / 1,218 | GV02 (1,343cc) | 26 / 838 | |
| HV03-1 (1,339cc) | 1,193kg, CVT, 2WD, 2001—2005 | 22 / 910 | GV03 (1,493cc) | 10 / 808 | #2 |
| HV03-2 (1,339cc) | 1,274kg, CVT, 2WD, 2005—2010 | 78 / 3,299 | | | |
| HV03-3 (1,339cc) | 1,191kg, CVT, 2WD, 2009—2013 | 163 / 5,156 | | | #3 |
| HV04 (1,339cc) | 1143kg, CVT, 2WD, 2010—2013 | 151 / 3,228 | GV04 (1,339cc) | 869 / 37,110 | #2 |
| HV05-1 (1,496cc) | 1,132kg, MT, 2WD, 2010—2012 | 56 / 1,821 | GV05 (1,496cc) | 64 / 2,623 | #3 |
| HV05-2 (1,496cc) | 1,140kg, MT, 2WD, 2012—2013 | 6 / 46 | | | #2 |
| HV06 (1,496cc) | 1,160kg, CVT, 2WD, 2010—2012 | 39 / 944 | GV06 (1,496cc) | 209 / 8,487 | #3 |
| HV07-1 (1,496cc) | 1,240kg, CVT, 2WD, 1997—2000 | 113 / 2,990 | GV07 (1,496cc) | 798 / 33,844 | #3 |
| HV07-2 (1,496cc) | 1,220kg, CVT, 2WD, 2000—2003 | 88 / 1,798 | | | |
| HV07-3 (1,496cc) | 1,282kg, CVT, 2WD, 2003—2012 | 397 / 12,990 | | | |
| HV07-4 (1,496cc) | 1,114kg, CVT, 2WD, 2011—2013 | 126 / 1,233 | | | |
| HV08-1 (1,797cc) | 1,386kg, CVT, 2WD, 2009—2012 | 494 / 11,910 | GV08 (1,797cc) | 147 / 7,650 | #3 |
| HV08-2 (1,797cc) | 1,485kg, CVT, 2WD, 2011—2014 | 47 / 643 | | | |
| HV08-3 (1,797cc) | 1,478kg, CVT, 2WD, 2011—2014 | 60 / 863 | | | |
| HV09-1 (2,362cc) | 1,606kg, CVT, 2WD, 2009—2013 | 29 / 687 | GV09 (2,362cc) | 8 / 282 | #1 |
| HV09-2 (2,362cc) | 1,640kg, CVT, 2WD, 2009—2012 | 14 / 348 | | | |
| HV09-3 (2,493cc) | 1,543kg, CVT, 2WD, 2011—2013 | 13 / 94 | | | #2 |
| HV10 (2,362cc) | 1,851kg, CVT, 4WD, 2001—2005 | 116 / 5,125 | GV10 (2,362cc) | 245 / 12,913 | #2 |
| HV11 (2,362cc) | 1,994kg, CVT, 4WD, 2006—2013 | 194 / 6,885 | GV11 (2,362cc) | 107 / 5,233 | #2 |
| HV12 (2,362cc) | 2,020kg, CVT, 4WD, 2003—2008 | 94 / 4,866 | GV12 (2,362cc) | 125 / 6,971 | #2 |
| HV13 (2,362cc) | 2,170kg, CVT, 4WD, 2011—2014 | 22 / 211 | GV13 (2,362cc) | 31 / 977 | #2 |
| HV14 (3,310cc) | 1,895kg, CVT, 4WD, 2005—2007 | 14 / 402 | GV14 (2,994cc) | 17 / 1,010 | #2 |
| HV15 (3,310cc) | 1,949kg, CVT, 4WD, 2005—2013 | 62 / 2,547 | GV15 (2,994cc) | 16 / 830 | #2 |
| HV16 (3,456cc) | 1,890kg, CVT, 2WD, 2006—2012 | 9 / 326 | GV16 (3,456cc) | 16 / 691 | #2 |
| HV17 (3,456cc) | 1,834kg, CVT, 2WD, 2008—2012 | 6 / 184 | GV17 (3,456cc) | 14 / 571 | #2 |
| HV18 (3,456cc) | 2,038kg, CVT, 2WD, 2009—2013 | 5 / 144 | | | #2, #4 |
| HV19 (3,456cc) | 2,100kg, CVT, 4WD, 2009—2013 | 9 / 218 | | | |

#1: GVs whose engine displacement is close to those of HVs are selected.
#2: GV and HV are lined up within the same vehicle name.
#3: Engine type of GV is the conventional variant of HV.
#4: The pieces of the counterpart GV information is not included in the database.

Fig. 5 shows the boxplot distribution of the real-world FC of HVs and their counterpart GVs. The boxplot comprises the minimum observation, lower quartile, median, upper quartile and the maximum observation of the real-world FC of the users who own each HV and GV type. It is confirmed from Fig. 5 that although the vehicle kerb weight of HVs are heavier than GVs, HVs have got the real-world FC advantages towards

GVs. These advantages become clear when the real-world FCs of the vehicles are divided by their kerb weight. Fig. 6 shows the boxplot distribution of the real-world FC expressed in [L/100km/t] unit. To evaluate the hybridisation effect on the real-world FC, $\gamma$, the rate of the real-world FC median of HV to its counterpart GV median, is calculated for each of the 27 HV types shown in Table 4 and the boxplot distribution of $\gamma$ is shown in Fig. 7. $\gamma$ ranges from 0.54 (HV08-1) to 0.79 (HV05-2) and its median is 0.64 (HV-9-3). This indicates that about 36% reduction on real-world FC can be expected by the hybridisation of GV in [L/100km/t] unit.

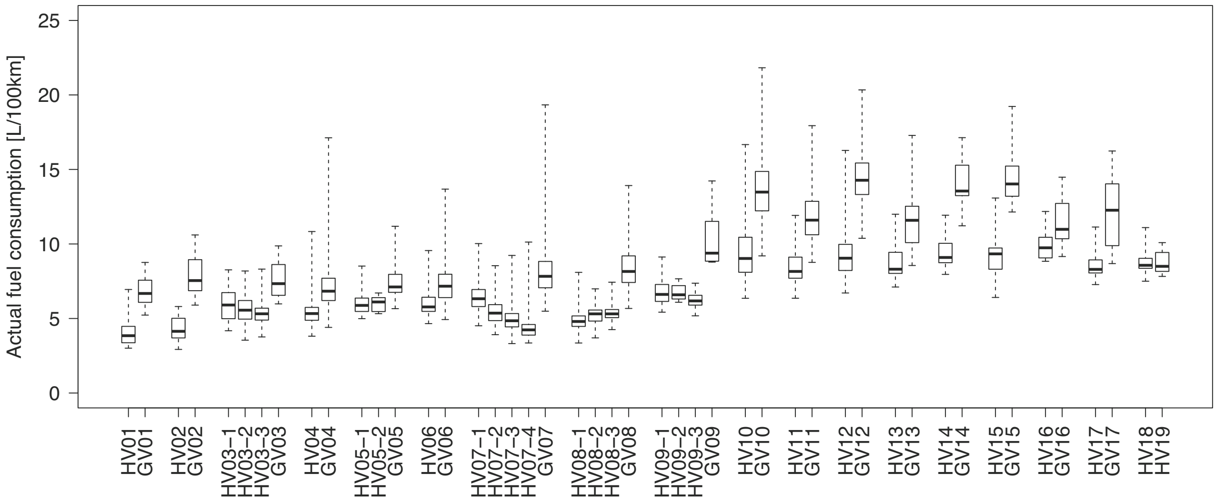


Figure 5: Boxplot distribution of the real-world FC of HVs and their counterpart GVs in [L/100km] unit

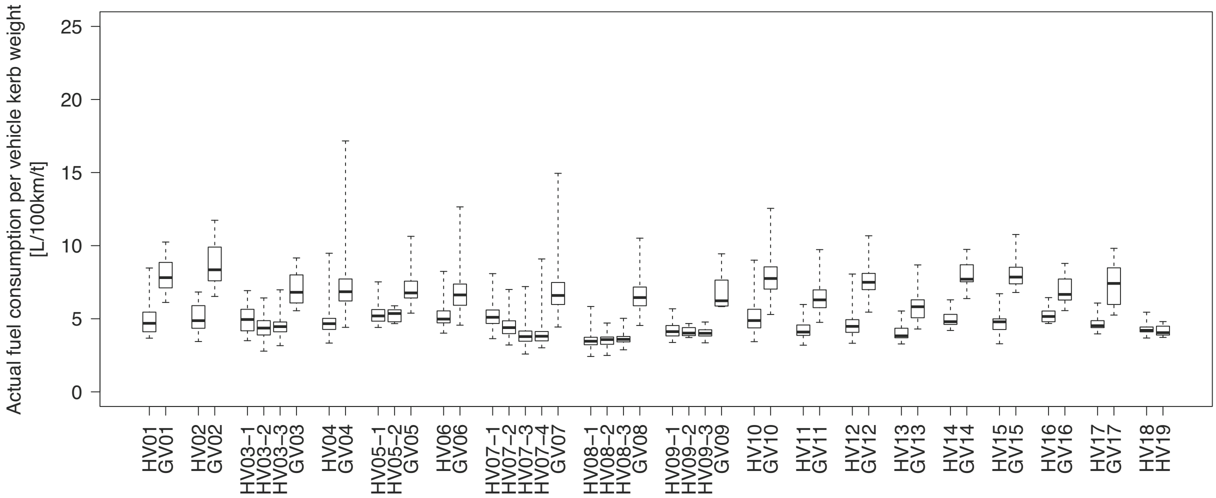


Figure 6: Boxplot distribution of the real-world FC of HVs and their counterpart GVs in [L/100km/t] unit

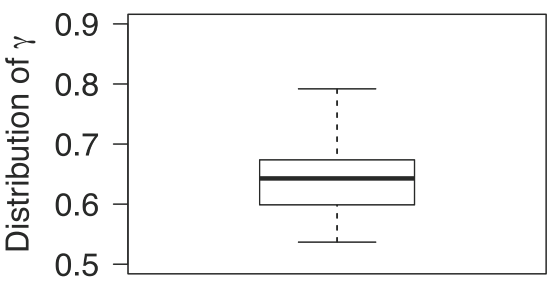


Figure 7: Boxplot distribution of $\gamma$

# 4 Conclusion

The real-world FE/FC database that was developed by using voluntarily reported FE/FC data from vehicle users and the vehicle specification database was used in this study to investigate the real-world FC performance of HVs and GVs as the conventional baseline in Japan. It is found from the relationship between the Japanese JC08 mode and the real-world FC that the FC performance of HV is better than that of GV but the divergence between type-approval and real-world FC tends to be greater than GV. It is also confirmed that HVs can be confirmed to demonstrate better real-world FC performance than GVs within the same vehicle weight class. From the boxplot distribution of the HV users' real-world FC observation and their counterpart GV users' observation, it can be expected that the real-world FC can be improved by 36% on average by hybridisation of GV models.

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