ISSN 2032-6653

Statistical Analysis of Fuel Consumption of Hybrid Electric Vehicles in Japan

Yuki Kudoh*, Keisuke Matsuhashi**, Yoshinori Kondo**, Shinji Kobayashi**,

Yuichi Moriguchi**, Hiroshi Yagita***

It is quite a well-known fact that there exists a gap between fuel consumption of vehicles measured by driving schedule test cycle and fuel consumption in actual use (actual fuel consumption). In order to investigate the actual fuel consumption statistically, we put focus upon the voluntary reported fuel consumption log data collected through an internet-connected mobile phone system from all over Japan and have been establishing an actual fuel consumption database. In this paper, actual fuel consumption of hybrid electric vehicles, together with those of internal combustion engine vehicles, in Japanese condition has been estimated.

Keywords: Energy Efficiency, Energy Consumption, Hybrid Electric Vehicle, Passenger Cars

1. INTRODUCTION

Within the "Kyoto Protocol Target Attainment Plan" approved by the Japanese Cabinet on 28th April 2005, it is assumed that CO2 emissions from the transport sector could be stabilized at a level of 15.1% above the emissions in 1990. Among the envisioned measures to reduce the emissions in transport sector, CO2 emissions cut effect by improving the fuel consumption (or fuel economy) of vehicles have got a large impact towards the total reduction. The targets for fuel consumption standards are provided in the revised Law Concerning the Rational Use of Energy (Energy-Saving Law, ESL) 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 industry.

According to the revised ESL, passenger vehicles sold in Japan in 2010 are expected to achieve the fuel consumption standards in Japanese 10.15 mode driving schedule stipulated for each vehicle inertia weight class. This translates into an average improvement in the fuel consumption of petrol fuelled passenger vehicles by 22.8% from the actual level of 1995. Amongst the vehicle technologies, hybrid electric vehicles (HEVs) are thought to be one of the promising technologies to improve fuel consumption and achieve the CO2 reduction target.

After the first commercial passenger HEV has brought into Japanese car market in 1997, vehicle manufactures have started to develop and sell various types of passenger HEVs and the number of passenger HEVs owned has been steadily increasing. According to Japan Automobile Research Institute [1], 10 types of HEVs have been sold in Japanese market and the number of passenger HEVs owned is estimated to be approximately 250,000 in FY 2005.

However, it is quite a well-known fact that there exists a gap between fuel consumption of vehicles measured by driving schedule test cycle and fuel consumption in actual use (actual fuel consumption). It is because the actual fuel consumption strongly depends upon where and how we drive, traffic conditions, weather or the maintenance situation of our vehicle, and any single driving schedule cannot simulate all the possible combinations of driver behaviour, traffic conditions, climate and car-care habits.

Hence it is not certain whether the CO2 reduction target can be achieved unless the precise actual fuel consumption of vehicles is reflected in the estimation, for the expected CO2 reduction amount is basically estimated based upon the fuel consumption standards in Japanese 10.15 mode driving schedule.

There are many studies that investigated the existing gap between the fuel consumption by driving schedule test cycle and the actual fuel consumption. For instance, Duoba et al. [2] have tested the "robustness" of fuel economy toward changes in vehicle activity for HEVs and their counterpart internal combustion engine vehicles (ICEVs) by applying various driving schedules on chassis dynamometer. In Japan, many studies have attempted to investigate the actual fuel consumptions

* National Institute of Industrial Science and Technology, 16-1 Onogawa, Tsukuba, 305-8569, JAPAN, e-mail: kudoh.yuki@aist.go.jp
** National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, 305-8506, JAPAN, e-mail: matuhasi@nies.go.jp; kondos@nies.go.jp; kobayashi.shinji@nies.go.jp; moriguti@nies.go.jp
*** Nippon Institute of Technology, 4-1 Gakuendai, Miyashiro-machi, Minamisaitama-gun, Saitama, 345-8501, JAPAN, e-mail: yagita@nit.ac.jp

ISSN 2032-6653

statistically that depends upon where and how they were driven through questionnaire surveys. However, most of those were unable to analyse them with statistical reliability under the limited number of examinees' data [3].

National Institute of Advanced Industrial Science and Technology (AIST) and National Institute for Environmental Studies (NIES) have been conducting a joint research programme to develop the Environmental Sustainable Transport scenarios that achieve CO2 reduction target set for the year 2020 and 2050 by the combination of technological innovation and demand change. In the project, we hold that wide spread of HEVs might be one the most feasible and effective options towards CO2 reduction in the year 2020 and are trying to comprehend the actual fuel consumption of various types of vehicles including HEVs.

Recently, the internet-connected mobile phone system has become wide spread in Japan and a variety of mobile phone contents are provided. In this project, we put focus upon the voluntary reported fuel consumption log data collected through the internet-connected mobile phone system from all over Japan and have been establishing an actual fuel consumption database. Although we have already reported some of the findings of actual fuel consumption that can be obtained from the database [4], we have updated the database by extending the data collection period of the fuel consumption log data from 24 months to 54 months (from October 2002 until March 2005). In this paper, a statistical analysis is carried out by our latest database and actual fuel consumption of passenger HEVs, together with passenger ICEVs, in Japanese condition has been estimated.

2. OUTLINE OF ACTUAL FUEL CONSUMPTION DATABASE

The actual fuel consumption database was established based upon the voluntary reported fuel consumption log data of vehicle users called "e-nenpi" and specification data of each model of vehicle. The outline of the database is shown in Fig. 1. The "e-nenpi" (which stands for "electronic fuel economy" in Japanese: http://e-nenpi.com) is an online service for the internet-connected mobile phone system provided by IRI Commerce and Technology Inc. that can manage pieces of information for car owners such as fuel consumption, preferable timing to change engine oil, etc. First of all, those who want to use the service have got to register and input the following five items: (1) zip code of one's residence, (2) vehicle model, (3) whether the mounted engine is turbocharged / supercharged (TC) or not (normal air intake, N/A,) (4) whether the transmission is manual (MT) or automatic (AT/CVT) [1] and (5) kind of fuel (unleaded petrol,

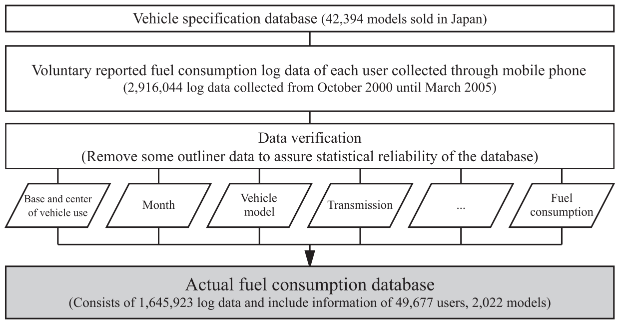


Fig. 1 Outline of the actual fuel consumption database

premium unleaded petrol, diesel or LPG) in the vehicle's tank. The fuel consumption data of the users are accumulated at the server by entering the amount of fuel put into the vehicle's tank and the odometer reading at the time they have fuelled through their mobile phone.

In addition to the actual fuel consumption database, we have collected the vehicle catalogue data sold in Japanese car market that are available on internet and build a vehicle specification database. It contains vehicle specification data of 42,394 vehicles. This database is used to obtain more detailed vehicle specification data that are not reflected in fuel consumption log data.

Although technological specifications may vary within the same model 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 cannot be specified from the log data. Hence the following values obtained from the vehicle specification database was adopted as some of the technological specifications of a model in the actual fuel consumption 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 fuel economy.

From 2,916,044 fuel consumption log data collected from October 2000 until March 2005, first of all those that satisfy the following criteria were extracted and aggregated by users and vehicle models in order to assure the statistical reliability of the database:

1. Base and centre of where the vehicle is used can be specified [2].
2. Passenger vehicles whose technological specifications can be identified from the vehicle specification database.
3. The refuelled amount is more than 10 litres and less than the fuel tank's capacity.
4. Mileage from the last time fuelled is more than 100 km.
5. Filled up rate γ of each fuel consumption log data is more than 60% and less than 100%. γ can be calculated by $\gamma = f / C$, where f [Litres] is the amount of fuel put into the tank and C [Litres] the

[1] Although the fuel consumption may be different by AT or CVT, they are grouped together within the database owing to a certain data restriction.

[2] It can be specified from the zip code of the registered user. Although the zip code is an essential item when registering, there are users who have entered it wrongly.

ISSN 2032-6653

fuel tank capacity.

6. Data that are obviously thought to have been entered wrongly or arbitrarily.
7. Data whose fuel economy is not determined as statistical outliers by conducting Grubbs' test for a critical level of 5% within the same vehicle model owned by a user.
8. Data of users who have fuelled more than 5 times within the period covered.
9. Data of users whose variance of fuel economy is less than 10 [(km/L)^2].

Then the extracted data are aggregated by vehicle model. Within the same model, if their types of engine (TC or N/A) or transmission (MT or AT/CVT) differ, they are treated as different models. Only those data that satisfy the following two additional criteria are used for the database.

10. Data of users whose average fuel economy are not determined as statistical outliers by conducting Grubbs' test for a critical level of 5% within the same vehicle model.
11. Data of models that are owned by more than 3 users.

Finally, 1,645,923 log data, which include information of 49,677 users and 2,022 models, were used to establish the database.

The database is consisted of 14 attributes: (a) base and centre of where the vehicle is used, (b) month, (c) manufacture of vehicle, (d) model of vehicle, (e) type of power train (conventional internal combustion engine or hybrid system), (f) kind of fuel (petrol, diesel or LPG), (g) type of engine (reciprocating engine or Wankel engine), (h) fuel injection type of engine (direct injection or not), (i) whether variable valve timing (VVT) system is adopted or not, (j) TC or N/A, (k) engine displacement, (l) MT or AT/CVT, (m) type of drive system (2WD or 4WD) and (n) vehicle weight. Vehicle models owned by users are classified into each attribute according to the technological specification of the vehicle model.

Actual fuel economy $FE_{i,j,...}$ [km/L] and actual fuel consumption $FC_{i,j,...}$ [L/100km] are calculated by Eq. 1 and Eq. 2 respectively, which is the same averaging approach adopted in [5], where *i,j,...* are either user or vehicle model or the attributes, $m_{i,j,...}$ [km] mileage from the last time fuelled and $f_{i,j,...}$ [Litres] the amount of fuel.

$$FE_{i,j,...} = \sum_{i,j,...} m_{i,j,...} / \sum_{i,j,...} f_{i,j,...} \quad (1)$$

$$FC_{i,j,...} = 100 / FE_{i,j,...} \quad (2)$$

Although it is assumed in Eq. 1 and Eq. 2 that the amount of fuel should be at the same level every time after refuelling, there may be users who do not fill up the fuel at filling stations. The "e-nenpi" system recommends the registered users to fill up the fuel at filling stations. In addition, only the data that satisfy the 11 criteria described above are used to establish the database. Fig. 2 shows the histogram of filled up rate γ of each fuel consumption log data. The average filled up rate of 1,645,923 log data is 76.8%. Since the fuel must be filled before the fuel tank gets completely empty, it can be said from Fig. 2 that most of the registered users fill up the fuel and the fuel tank level of their vehicle should be almost the same every time.

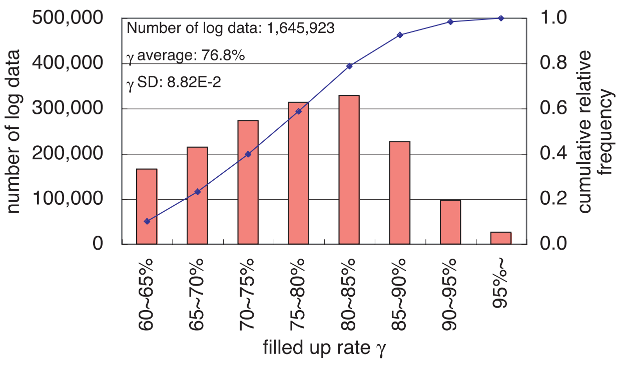


Fig. 2 Histogram of filled up rate γ

Table 1 Abbreviations for vehicle types

Abbreviation	Vehicle type
PICEV	Petrol fuelled passenger ICEV
PICEV-LP	Light passenger PICEV (Kei-car)†
PICEV-P	Passenger PICEV
PICEV-PW	Passenger PICEV with Wankel engine
HEV	Passenger HEV

†A Japanese category of small vehicles. Its physical size and engine power is regulated as follows: maximum length : 3.39m, maximum width: 1.48m, maximum height: 2m, maximum displacement: 660cc, maximum power: 64hp.

3. STATISTICAL ANALYSIS OF ACTUAL FUEL CONSUMPTION

Authors have been carrying out statistical analysis of the actual fuel consumption from various points of view through the actual fuel consumption database. In this section, actual fuel consumption of passenger HEVs and petrol fuelled passenger ICEVs are picked up.

The abbreviations for vehicle types used hereafter are shown in Table 1.

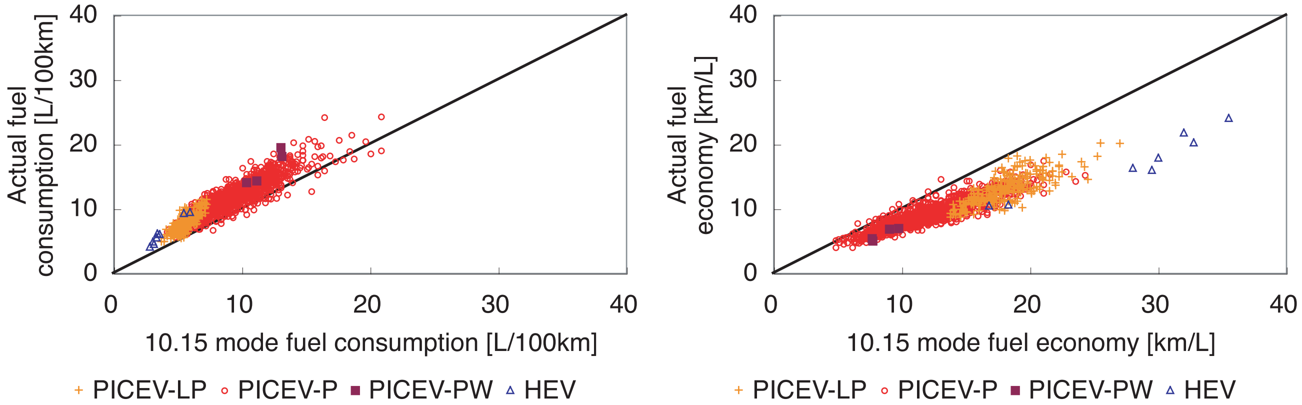
3.1 10.15 Mode Fuel Consumption and Actual Fuel Consumption

Fig. 3 shows the relationship between 10.15 mode and actual fuel consumption (or economy) and Table 2 shows the results of linear regression analysis

$$E_{actual} = a \cdot E_{10.15} + b \quad (3)$$

where E_{actual} is actual fuel consumption [L/100km] or actual fuel economy [km/L] and $E_{10.15}$ 10.15 mode fuel consumption [L/100km] or actual fuel economy [km/L]. If the plot is on the line drawn upon Fig. 3, it means that actual fuel consumption or economy performance is exactly the same as 10.15 mode fuel consumption or economy. From Fig. 3 and Table 2, it can be said that although the gap of HEVs between 10.15 mode and actual fuel consumption may be larger than that of PICEV-Ps, fuel consumption performance of HEVs in actual use is absolutely better than PICEV-Ps.

ISSN 2032-6653

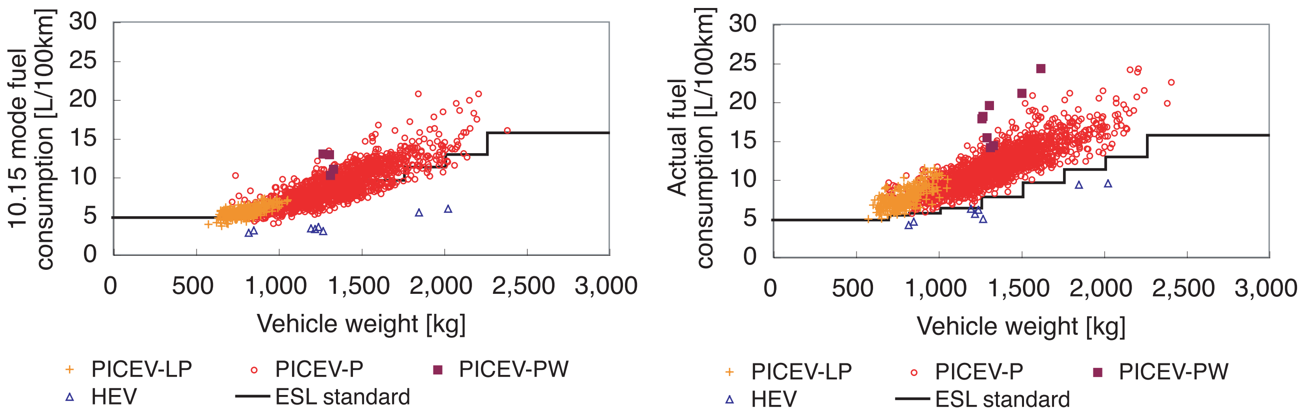


(a) Fuel consumption (b) Fuel economy

Fig. 3 10.15 mode fuel consumption (economy) and actual fuel consumption (economy)

Table 2 Results of regression analysis $E_{actual} = a \cdot E_{10.15} + b$ in Fig.3

		Fuel consumption [L/100km]			Fuel economy [km/L]		
		a	b	R^2	a	b	R^2
PICEV		1.04	2.20	0.855	0.638	1.55	0.856
	PICEV-LP	1.50	-0.553	0.609	0.743	-0.324	0.592
	PICEV-P	1.01	2.488	0.825	0.622	1.73	0.826
	PICEV-PW	1.87	-5.63	0.907	0.939	-1.85	0.915
HEV		1.71	-0.246	0.959	0.697	-2.18	0.920



(a) 10.15 mode fuel consumption (b) Actual fuel consumption

Fig. 4 Vehicle weight and fuel consumption

3.2 Vehicle Weight and Actual Fuel Consumption

Fig. 4 shows the relationship between vehicle weight and fuel consumption. The lines drawn upon the figures represent the 2010 target fuel consumption standard set in the revised ESL and thus the plots under the lines means that they have achieved the 2010 standard. Within the same vehicle weight class, HEVs can be confirmed to demonstrate better fuel consumption performance than PICEVs both in 10.15 mode and in actual fuel consumption. It can also be said from Fig. 4 that there are indeed models that have achieved the ESL standard in 10.15 mode fuel consumption. From our database, however, only the HEV models can achieve the target not only in 10.15 mode but also in actual fuel consumption.

Using the plots in Fig. 4, a linear regression analysis described by Eq. 4 has been undertaken, whose results are shown in Table 3.

Table 3 Results of regression analysis $FC_{actual} = c \cdot w + d$ in Fig.4 (b)

		Fuel consumption [L/100km]		
		c	d	R^2
PICEV		8.10E-3	0.965	0.758
	PICEV-LP	9.09E-3	0.493	0.471
	PICEV-P	8.43E-3	0.442	0.720
	PICEV-PW	2.12E-2	-10.7	0.600
HEV		4.64E-3	0.238	0.925

$$FC_{actual} = c \cdot w + d \tag{4}$$

where FC_{actual} is actual fuel consumption [L/100km] and w vehicle weight [kg]. Eq. 4 and Table 3 can be used for estimation of the actual fuel consumption for each type of vehicles if its vehicle weight is given.

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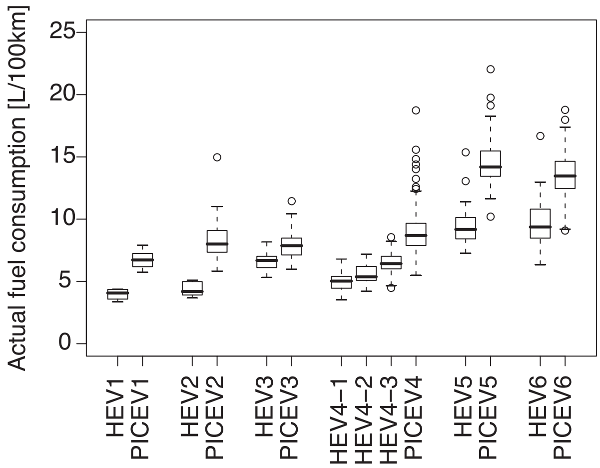
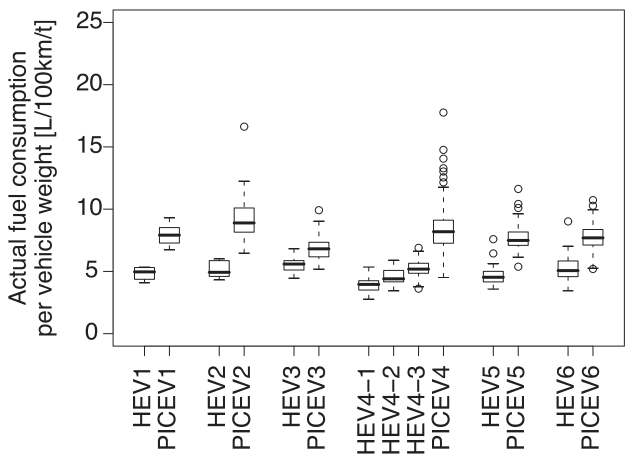
Table 4 Selection of HEVs and their counterpart PICEVs

HEV type	Specifications (Hybrid type, Engine displacement, Vehicle weight, Transmission type, Drive train type, Model year)	Power weight ratio of motors [kg/PS]	Number of HEV users / log data	Counter-part PICEV type	Number of PICEV users / log data	Remarks
HEV1	Power assist hybrid, 995cc, 820kg, MT, 2WD, 1999~	66	4 / 66	PICEV1	15 / 353	#1
HEV2	Power assist hybrid, 995cc, 850kg, CVT, 2WD, 1999~	63	12 / 379	PICEV2	77 / 2,175	
HEV3	Power assist hybrid, 1,339cc, 1,190~1,200kg, CVT, 2WD, 2001~2005	88	7 / 144	PICEV3	89 / 3,132	#2
HEV4-1	Full hybrid, 1,496cc, 1,250~1,300kg, CVT, 2WD, 2003~	19	43 / 671	PICEV4	626 / 18,466	#3
HEV4-2	Full hybrid, 1,496cc, 1,220kg, CVT, 2WD, 2000~2003	27	35 / 1,108			
HEV4-3	Full hybrid, 1,496cc, 1,240kg, CVT, 2WD, 1997~2000	30	44 / 1,203			
HEV5	Full hybrid, 2,362cc, 2,000~2,050kg, CVT, 4WD, 2003~	48	20 / 366	PICEV5	54 / 1,502	#2
HEV6	Full hybrid, 2,362cc, 1,840~1,860kg, CVT, 4WD, 2001~2005	44	51 / 1,447	PICEV6	128 / 4,399	

#1: PICEVs whose engine displacement is nearest to those of HEVs have been chosen.
#2: HEV and PICEV type are lined up within the same vehicle name.
#3: HEVs have the same vehicle name but their vehicle types are different. Engine type of PICEV is conventional variant of HEVs.



(a) Actual fuel consumption



(b) Actual fuel consumption by vehicle weight

Fig. 5 Actual fuel consumption of HEVs and their counterpart HEVs

3.3 Actual Fuel Consumption of HEVs and Their Counterpart Petrol Fuelled ICEVs

In this subsection, actual fuel consumptions of passenger HEVs are compared to their counterpart passenger PICEVs. We have got eight different models of HEVs in our database. Table 4 shows HEVs and their counterpart PICEV-Ps chosen for comparison in this paper. They are chosen from the same vehicle manufacture with almost the same model year.

Fig. 5 depicts the distribution (boxplot) of the actual fuel consumption of HEVs and their counterpart PICEVs. The boxplots are consisted of the smallest non-outlier observation, lower quartile, median, upper quartile and largest non-outlier observation and the outliers are plotted circle. It can be confirmed by Fig. 5 (a) that HEVs have got advantage towards PICEVs in actual fuel consumption although the weights of vehicles are heavier than PICEVs. If the fuel consumption is divided by vehicle weight, as shown in Fig. 5 (b), the advantages of HEVs become much clear. There exists a difference of actual fuel consumption by vehicle weight also within HEVs as shown in Table 5.

Table 5 Comparison of HEVs to their counterpart PICEVs in [L/100km/t] unit

HEV type	Median of HEV / median of its counterpart PICEV
HEV1	0.63
HEV2	0.55
HEV3	0.82
HEV4-1	0.48
HEV4-2	0.54
HEV4-3	0.63
HEV5	0.61
HEV6	0.66

The rate of fuel consumption of HEV to their counterpart PICEV is 0.62 on average with the range of 0.48 to 0.82 in [L/100km/t] unit. Some of the imaginative reason for this may be stated as follows:

- Difference in body shape and vehicle weight. Vehicle specifications such as drag coefficient, frontal area of vehicle and vehicle weight affect to running resistance and consequently fuel consumption of a vehicle.

ISSN 2032-6653

- Difference in hybrid control system. The rate of use between motor and engine differs depending upon the mounted hybrid system such as the power train structure or the degree of hybridization. Therefore actual fuel consumption varies by the hybrid system mounted.
- Power weight ratio of motors. Although there are some exceptions, it can be said that actual fuel consumption by vehicle weight improves in proportion to the power weight ratio of motors if the third row of Table 4 is contrasted with Fig. 5 (b). By mounting motor with high power, fuel consumption can be improved by widely assisting the engine in low efficiency region.

The actual fuel consumption of vehicles strongly depends upon where and how we drive. The former would be whether we drive a car in congested traffic in urban areas or in smooth traffic in rural areas and the latter would be how aggressive we drive or whether the start condition of the car we use is cold or hot.

There may be some macroscopic parameters that can explain the difference in actual fuel consumption distribution shown in Fig. 5 for the former case. One of those can be average travel velocity of vehicle that varies by where it is driven. We are planning to continue to investigate how these parameters would affect to actual fuel consumption.

Besides, there may be more good reasons from the viewpoint of automotive engineering what kind of automotive technology, vehicle vehaviour or starting condition of a car would affect to fuel consumption of these vehicles. However, since our database has been established to estimate actual fuel consumption of vehicles from a macroscopic point of view, more detailed research is required to see further trends of actual fuel consumptions by using other data sources.

4. SUMMARY

In order to investigate the actual fuel consumption with statistical reliability, we put focus upon the voluntary reported fuel consumption log data collected through internet-connected mobile phone system from all over Japan and have established an actual fuel consumption database. In this paper, a statistical analysis is carried out through the database and actual fuel consumption of passenger HEVs, together with passenger ICEVs, in Japanese condition has been estimated from a macroscopic point of view.

The estimated results show that although the existing gap of HEVs between 10.15 mode and actual fuel consumption is larger than that of PICEVs, fuel consumption itself of HEVs in actual use is absolutely better than PICEVs. It can be confirmed that increase in vehicle weight owing to hybrid systems does not strongly affect to fuel consumption of HEVs from the comparison of actual fuel consumption by vehicle weight of HEVs to their PICEVs counterpart.

It is not only the vehicle specifications but also where and how we drive that affect to actual fuel consumption of vehicles. We are planning to continue to investigate how these elements would have influence towards actual fuel consumption of vehicles.

ACKNOWLEDGEMENT

This project was supported by the Global Environment Research Fund S-3-5: “Long-term CO2 reduction strategy of transport sector in view of technological innovation and travel demand change” by the Ministry of the Environment, Japan.

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BIOGRAPHIES

Yuki Kudoh, Dr.-Eng., Research Scientist, Environmental Efficiency Research Team, Research Center for Life Cycle Assessment, National Institute of Advanced Industrial Science and Technology.

Keisuke Matsuhashi, Dr.-Eng., Senior Researcher, Transportation and Urban Environment Section, Social and Environmental Systems Division, National Institute for Environmental Studies.

Yoshinori Kondo, Dr.-Eng., Senior Researcher, Transportation and Urban Environment Section, Social and Environmental Systems Division, National Institute for Environmental Studies.

Shinji Kobayashi, Dr.-Eng., Section Leader, Transportation and Urban Environment Section, Social and Environmental Systems Division, National Institute for Environmental Studies.

Yuichi Moriguchi, Dr.-Eng., Director, Research Center for Material Cycles and Waste Management, National Institute for Environmental Studies.

Hiroshi Yagita, Dr.-Eng., Ass. Prof., Department of Systems Engineering, Faculty of Engineering, Nippon Institute of Technology. He holds concurrent post of Team Leader, Energy Systems Analysis Team, Research Center for Life Cycle Assessment, National Institute of Advanced Industrial Science and Technology.