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Effectiveness of Plug-in Hybrid Electric Vehicle Validated by Analysis of Real World Driving Data

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Abstract

In recent years, the usage of various alternative energies is considered from a viewpoint of CO2 emission reduction. Toyota Motor Corporation considers that Plug-in Hybrid Electric Vehicles (PHEVs) is the best practical solution, and has launched Prius Plug-in Hybrid in January 2012.

Prior to this, in December 2009, Toyota sold 650 PHEVs through lease programs for validation testing in Europe, the U.S. and Japan. As a result, not only the fuel reduction effect in case of real market usage was confirmed, but also the relationship between frequency of charging and fuel reduction effect.

This paper discusses the analysis of the validation test results.

Keywords: PHEV, battery charge, infrastructure

1 Introduction

Various issues related to automobiles, such as reducing CO2 emissions, resolving energy security problems (i.e., instability in the supply of fossil fuels), and reducing emissions of air pollutants in urban areas, must be solved in order for people to continue to enjoy driving, the convenience of moving freely, and the pleasure of having the comfortable moveable space that automobiles currently provide. For the past several years, hybrid vehicles (HVs) have been one countermeasure to these issues. The fuel consumption reduction effects of HVs (i.e., those achieved through regenerative braking, idle stop when the vehicle is not moving, and EV driving at low and/or constant speeds) have achieved major improvements in fuel efficiency and reductions in exhaust emissions compared to a conventional gasoline vehicle. In addition to these merits, utility and reliability are now the same as a conventional vehicle, and recently the number of HVs sold has increased drastically as prices have fallen (Figure. 1). Moreover, HVs require absolutely no additional infrastructure, and it is thought that this was a large factor in making them relatively acceptable throughout the world.

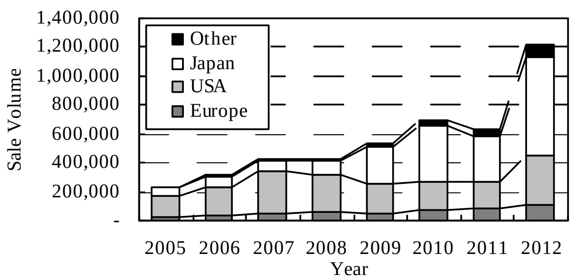


Figure 1. Sales Volume of Hybrid Vehicles

Furthermore, the introduction of electric vehicles (EVs) is a possible means of reducing CO2 and other exhaust emissions. By using electric power from the power grid, it is possible to reduce emissions of CO2 and air pollutants to zero during driving. However, even when using the latest Lithium-ion battery technology, energy density is limited to about 1/50th of that of fossil fuels, and the cruising range on a single charge is rather short. If the battery size is increased to reach the cruising range equivalent to a gasoline vehicle, large sacrifices must be made to the cabin and luggage space. Also, larger batteries lead to drastic increases in the weight and cost of the vehicle, and therefore are not practical. Additionally, charging a large capacity battery from an external source in a short period of time would require a DC external charger with high electric output capacity, needing dedicated infrastructure. Accordingly, when considering these limitations, it appears that EVs probably will not totally replace the conventional gasoline vehicle, now or in the near future. It is assumed that, in the short term, the EV will function as a commuter vehicle that covers short distances.

A PHEV combines the merits of an EV, since it has zero emissions during driving with electric power, with the merits of a HV, since it does not sacrifice any of the practicality of a standard vehicle. For example, cruising range is equal to or better than that of a conventional gasoline vehicle. This paper discusses the PHEV system used in the Prius plug-in hybrid, the first PHEV mass-produced by Toyota Motor Corporation.

2 CHARACTERISTICS AND MERITS OF PHEVS

The unique characteristics of PHEVs are further described below. As discussed earlier, the PHEV combines the merits of both EVs and HVs. One approach to the PHEV system design is to increase the capacity of the battery from that of the existing HV and install an on-board charger to the vehicle. Initially, after a full charge of the battery, a PHEV configured in this way will run primarily on electric energy. After the battery is depleted, the engine is operated intermittently, as a HV normally runs. By configuring the system in this way, the vehicle is primarily an EV for short distances, and it can run as a HV with the engine for long distances after the battery is depleted (Figure. 2). This gives the vehicle cruising range equivalent to a conventional gasoline vehicle or a HV and ensures utility and convenience. Furthermore, since an EV cannot run when the battery is depleted, it is necessary to arrive at a charging point before this happens. For this reason, it is difficult to use up all of the energy in the installed battery when driving with an EV. However, a PHEV differs from an EV in that the driver can use up all of the battery energy without hesitation because the vehicle can be driven with the engine even if the battery is depleted (Figure. 3). This is another advantage of the PHEV.

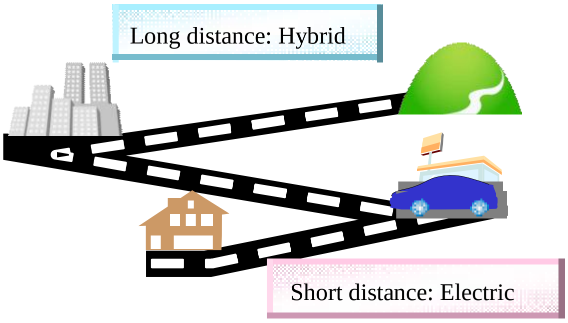


Figure 2. Concept of PHEV

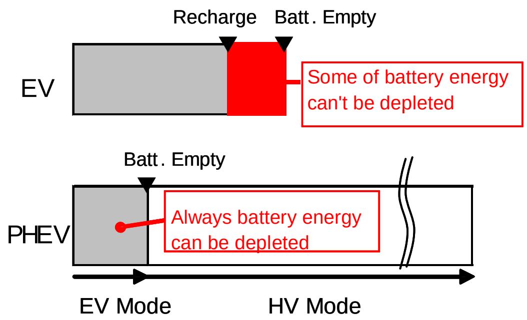


Figure 3. The Advantage of PHEV

A PHEV has two driving modes. After the battery has been fully charged, the vehicle normally operates in EV mode, in which electricity is the primary source of drive energy. In EV mode and normal driving conditions, PHEV performance is similar to that of an EV. Depending on the PHEV system operation, even during EV mode, the engine might operate to supply driving power when a large amount of power is necessary for rapid acceleration or high speed cruising. The other driving mode is HV mode, which starts after the battery is depleted. In this mode, the engine is used as the primary source of drive energy, and the system is operated so that the battery state of charge (SOC) is maintained around the middle of controlled value that is programmed in advance, in the same way as a HV. These are shown in Figure 4. In this way, once the battery energy is depleted and the vehicle changes to HV mode, sufficient driving range is ensured, depending on the fuel amount in the tank as with a conventional HV. EV mode is sometimes called CD mode which is the abbreviation for Charge Depleting mode, and HV mode is called CS mode which is the abbreviation for Charge Sustaining mode. In this paper these two terms (i.e. EV mode and HV mode) are mainly used to emphasize the PHEV's mode of operation.

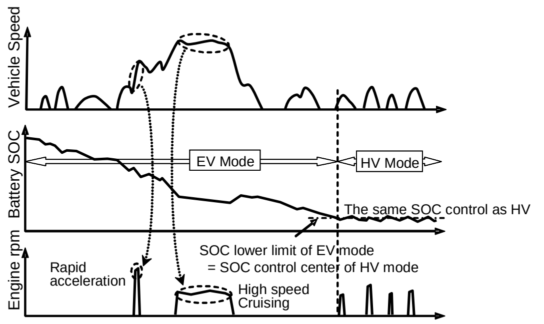


Figure 4. PHEV System Operation

3 RESULTS OF VALIDATION TESTS

Prior to this development, validation testing of PHEVs has been performed since December 2009 in the U.S., Europe and Japan, and the findings were useful in the development of this system. The EV range was set at 21.7km and the vehicle achieved CO2 emissions equivalent to 59g/km under the New European Driving Cycle (NEDC).

The results of the validation tests are described below. More than 600 vehicles were tested in various locations around the world and data related to driving and charging was recovered from each vehicle for analysis. The analyzed data from vehicles tested in France, the U.S. and Japan was then compared. The results for France were obtained from the test performed in Strasbourg, which involved 70 vehicles and was the largest test performed around the world. Table 1 outlines the scope of the data obtained in each region.

Table 1. Outlines of the Data Collected

Parameter	France	USA	Japan
No. of vehicle	67	65	145
Starting date	2010/4/15～	2010/6/1～	2009/12/8～
Mileage	1,302,885 km	595,510 km	1,262,363 km
Average Mileage per year	19,000 km	13,400 km	9,500km
Trips (times)	108,025	53,397	167,884
Charging Event (times)	20,821	10,672	37,448

3.1 Distance per Trip

Figure 5 shows the distribution for driving distance per trip in each region.

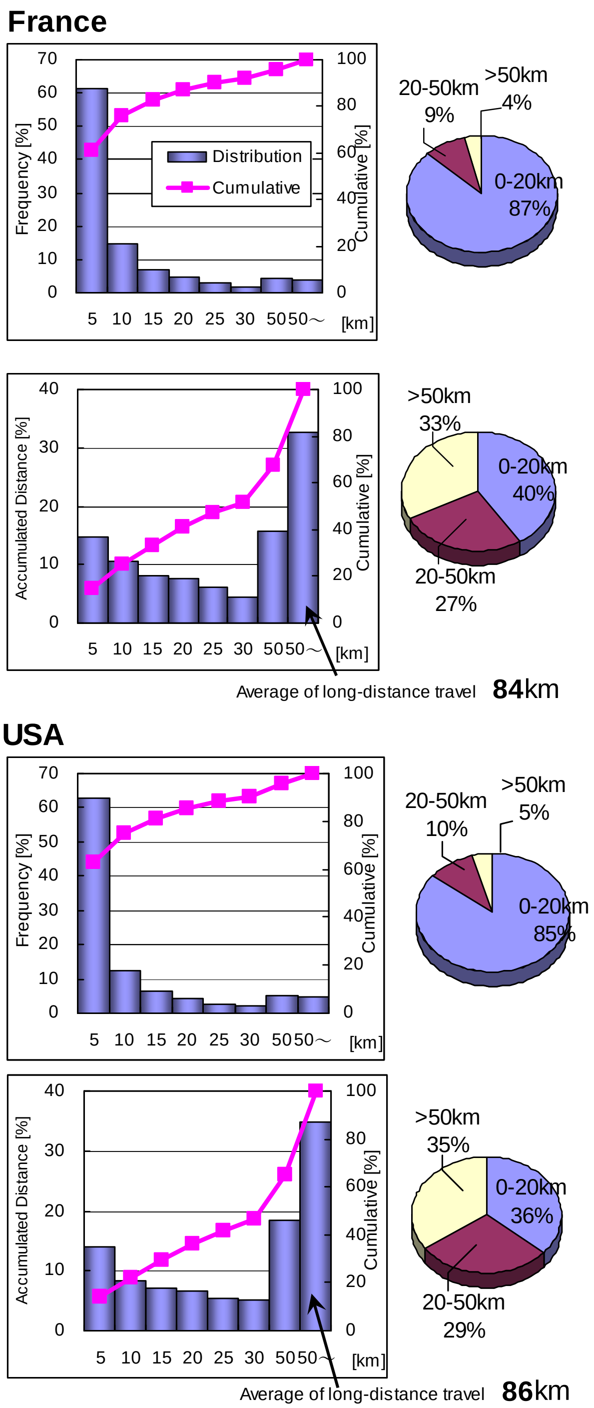


Figure 5(1). Distance per Trip

(Upper: Frequency Lower: Distance)

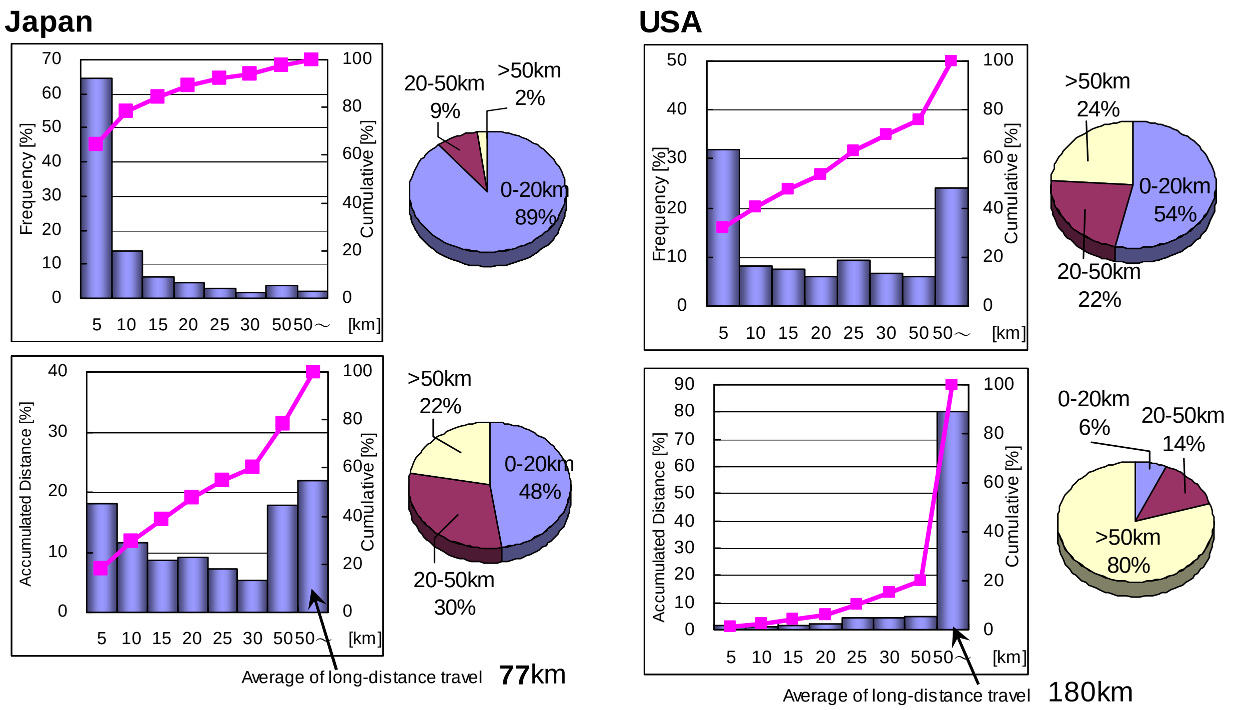
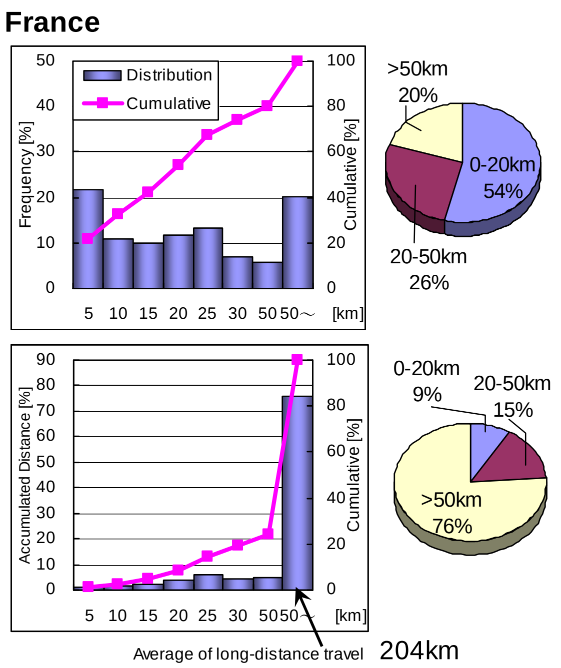


Figure 5(2). Distance per Trip

(Upper: Frequency Lower: Distance)

3.2 Distance per Charge

Figure 6 shows the frequency for driving distance per charge and the per-charge integrated driving distance.



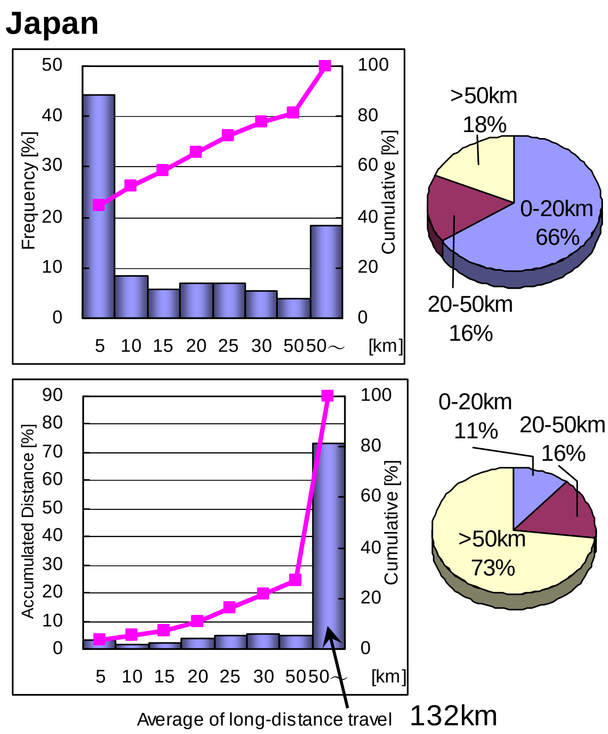


Figure 6. Distance per Charge

(Upper: Frequency Lower: Distance)

Here, the driving distance per charge is defined as the distance between one charge and the next charge. In each region, a high proportion of the distance per charge exceeded 50km (70 to 80%). When the distance per charge exceeded 50km, the average per-charge distance in France, the U.S.

and Japan was 204km, 180km and 132km, respectively. This shows that drivers were charging the PHEV only after a number of trips. When the charging frequency decreases, the number of trips per charge increases. This has the same effect as increasing the frequency of long-distance trips per charge.

3.3 Vehicle Speed

Figure 7 and 8 show the distribution for vehicle driving speed in each region. In France and the U.S., the vehicles are used both in city and on highway. Therefore, there are two peaks, one at high and one at low speed. In Japan, the vehicles are mainly used in the city and less driven at high speed. This explains the relatively high share of short-trips.

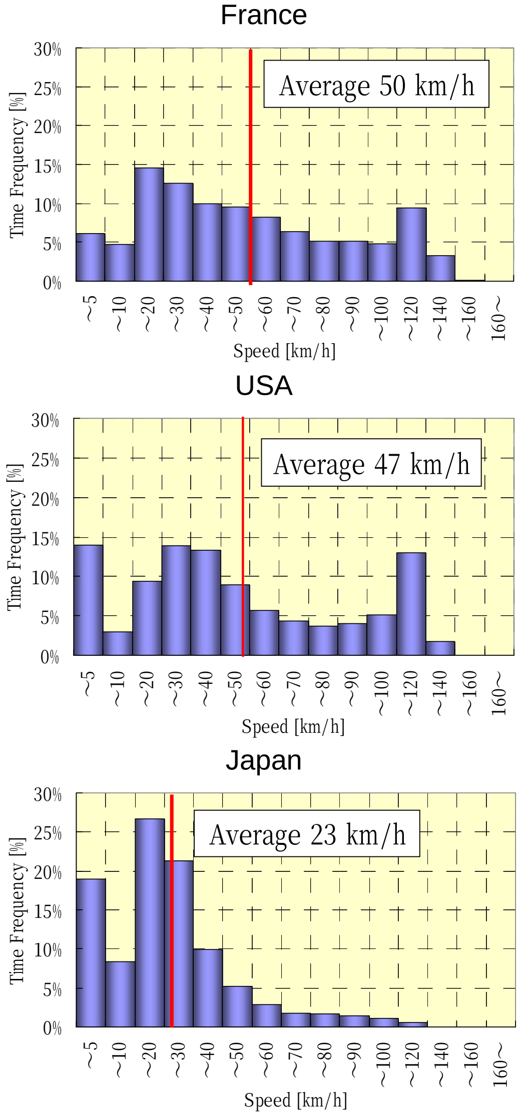


Figure 7. Vehicle speed (Time Frequency)

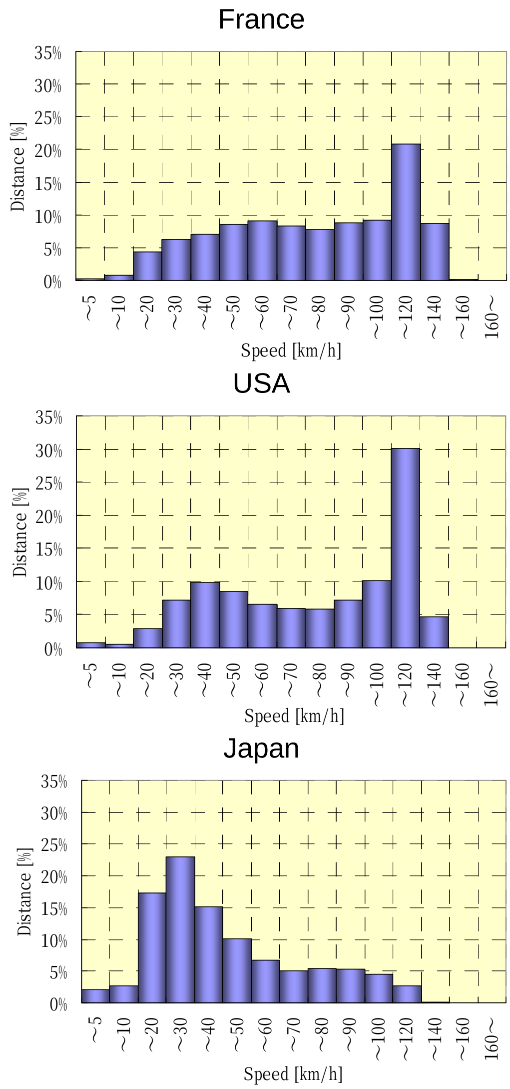


Figure 8. Vehicle speed (Distance)

3.4 Daily charging frequency

Figure 9 shows the distribution of daily charging frequency. The number of charging events per day in France is a little higher than the U.S. and Japan. Strasbourg has superior infrastructure, so that vehicles can be charged both at home and work.

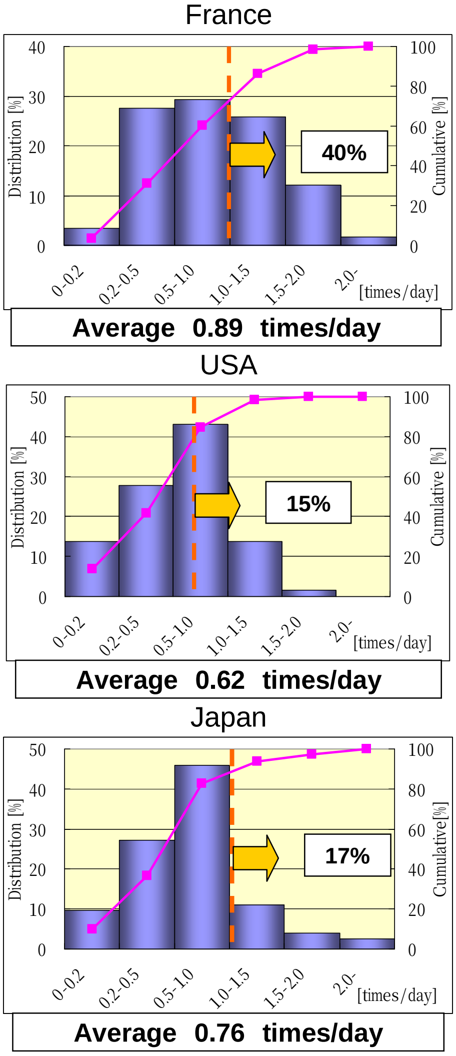


Figure 9. Daily charging frequency

3.5 Charging Proportion and fuel efficiency

Figure 10 shows the daily average number of charges and fuel consumption for each vehicle. The data is organized in sequence starting from the vehicle with the highest number of charges.

The graphs indicate that, in each region, the vehicles that were charged most frequently tended to have the best fuel consumption. However, large differences were observed in the number of charges per user in each country. More than half of the users charged the vehicle less than once per day. This generated the large gap in the fuel consumption reduction effect.

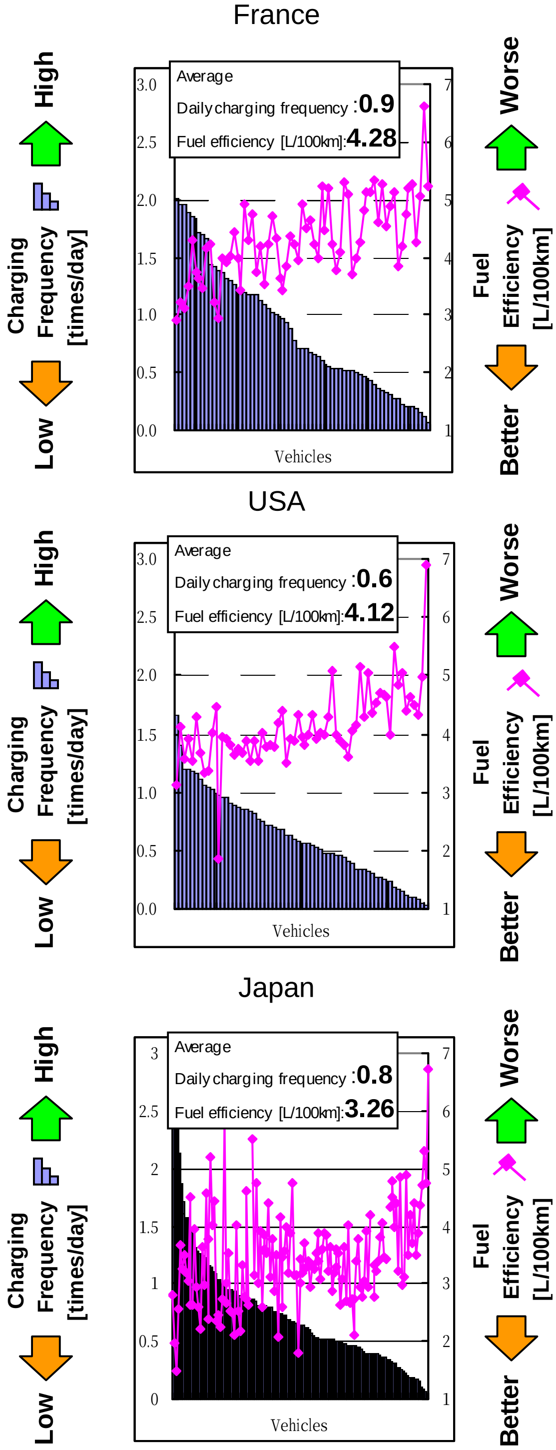


Figure 10. Daily Average Number of Charges and Fuel Consumption

3.6 Fuel consumption reduction effect

Figure 11 shows the fuel consumption reduction effect for each driving distance per charge, compared to a conventional internal combustion engine (ICE) vehicle. The fuel consumption of the

ICE vehicle was calculated from the driving distance and the fuel efficiency of the ICE vehicle, assuming that the ICE vehicle was driven the same distance as the PHEV. The fuel efficiency value used was the average value for the same class of automatic transmission (AT) ICE vehicles calculated by actual driving in each country. The results confirmed a large fuel consumption reduction effect in each region.

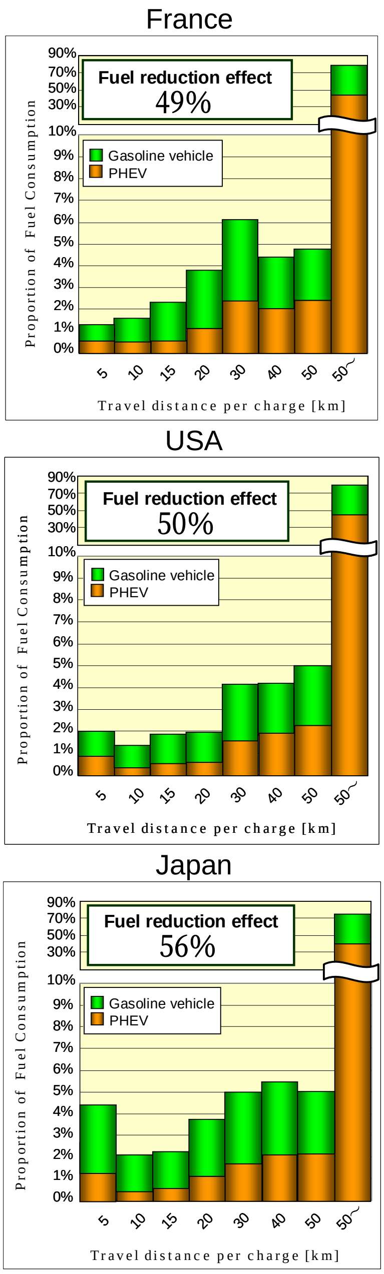


Figure 11. Fuel Consumption Reduction Effect

It has been confirmed by actual verification tests in Europe, the U.S. and Japan that a PHEV with approximately 20km EV range has the potential of lowering the fuel consumption.

3.7 Fuel reduction effect of each vehicle

Figure 12 shows the relationship between charging frequencies, EV drive ratio and fuel efficiency in France. These vehicles were selected in terms of different charging frequency.

Charging frequency is 1.6 times per day for driver A, 1.0 times per day for driver B and 0.2 times per day for driver C. Driver A with 60% EV drive reduces his fuel consumption by 69% compared to a gasoline vehicle with similar performance. On the other hand driver C with 2% EV drive reduces his fuel consumption by 33%. The fuel consumption for driver C is almost same as a HV.

In this validation test, the driver who charged the vehicle frequently achieved high fuel consumption reduction effects.

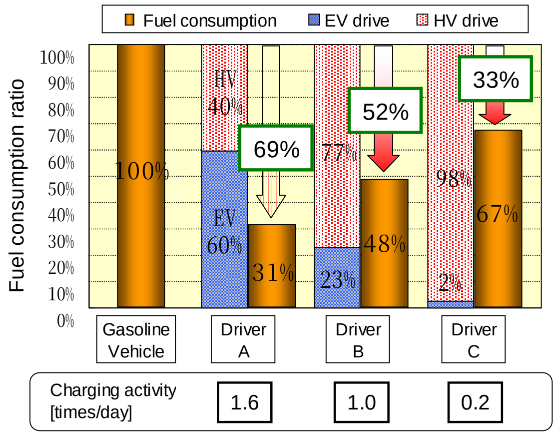


Figure 12. Proportion of EV drive and Fuel reduction effect of each vehicle (France)

4 STUDY OF CHARGING INFRASTRUCTURE LOCATION

4.1 GPS logger data

This part will look into the results and analysis based on information collected by the GPS data loggers.

GPS loggers were installed on some vehicles which were used in validation tests all around the world, so that we could determine the location of the vehicle and the charging behavior in detail.

Even if the number of vehicles for analysis was changed, still the data from the GPS loggers can reasonably represent the fuel reduction effect (Figure. 13).

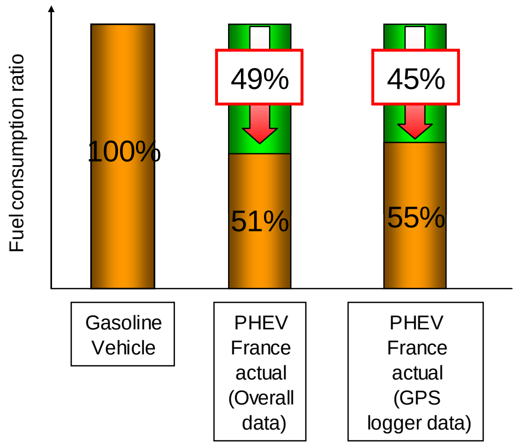


Figure 13. Fuel reduction effect by PHEV compared to conventional vehicle

4.2 Validation test in Strasbourg

GPS loggers were installed on 22 out of 70 vehicles in Strasbourg.
Charging stations were also installed at either work or home. In addition to these, Public charging stations were installed at 13 points in Strasbourg.

4.3 Frequency of charging at Home or Work

Figure 14 indicates the relationship between the vehicles parking locations and frequency. The frequency of parking at home and at work is high, respectively 23% and 19% for totally 42%. Parking at other locations was used less than 3 times.

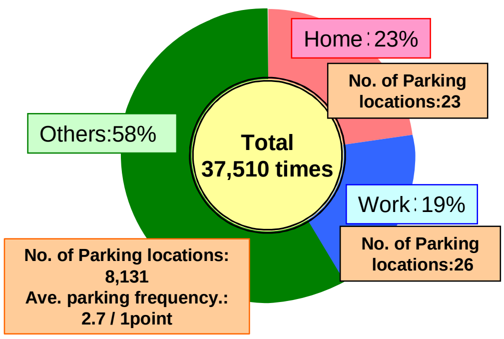


Figure 14. Parking location distribution

Figure 15 shows the distribution of parking duration at each location. At home or work, the vehicle is mostly parked for 180 minutes or more.

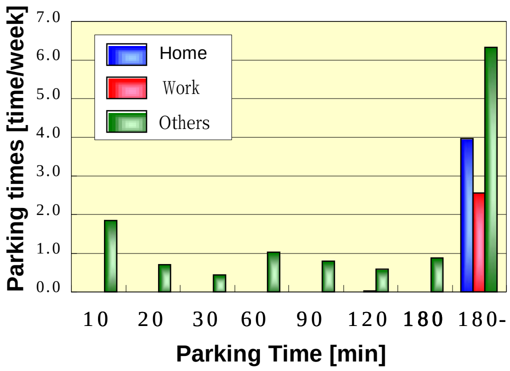


Figure 15. Frequency of Parking Time

According to these results, the most preferable place to charge the vehicle is at home or work.

4.4 Fuel consumption reduction effect by charging

To study the fuel consumption reduction effect by charging, we assume that the fuel reduction effect in cases where no charging occurs at all is 0%, and in cases where charging occurs at every trip is 100%. The fuel reduction at 0% is the same as a HV.
The fuel reduction effect by charging was 55% in France validation test (Figure. 16).

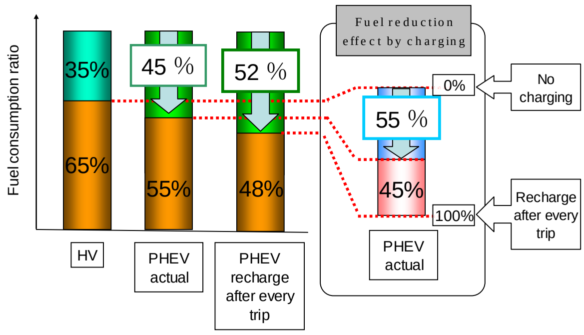


Figure 16. Fuel reduction effect by charging

4.5 Fuel consumption reduction effect by charging at Home and Work

The result in previous section includes charging at home or at work but vehicles were not necessarily charged at these locations when parked. The ratio of charging frequency with respect to the number of parking frequency at home and work is about 47% in the validation test.
We can calculate that 78% of the reduction effect is achieved by charging after every trip at home

and work. This means that charging at both home and work can cover 78% of the maximum charging effect (Figure. 17).

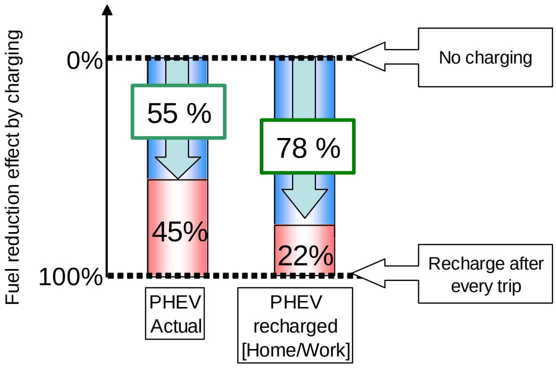


Figure 17. Fuel reduction effect by charging at Home and Work

4.6 Public charging infrastructures

In order to clarify the effectiveness of public charging infrastructure, we studied the driving route and parking activity of all 22 vehicles from the Strasbourg users. We identified 4 parking locations in shopping areas where many people visit and stay for a certain time (Figure. 18).

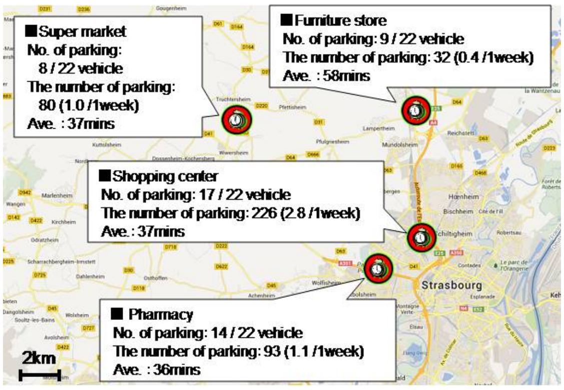


Figure 18. Parking areas often used in Strasbourg, France

4.7 Fuel consumption reduction effect by charging where vehicles are parked frequently

It is expected that if vehicles were charged during the parking at these 4 locations, the charging frequency increases effectively. We estimate that the fuel reduction effect by charging can be increased from 55% to 63% by charging at these 4 additional locations (Figure. 19).

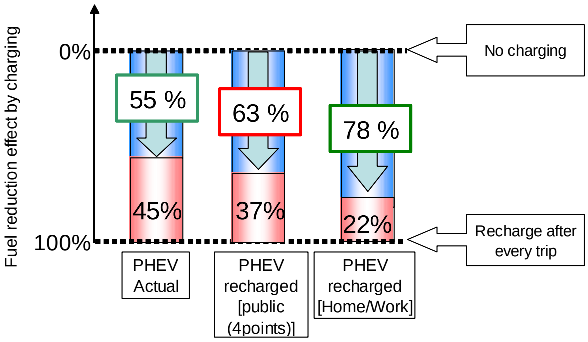


Figure 19. Fuel consumption reduction effect by charging at identified parking areas

Some users cannot have easy access to a charging point at home or work. In such a case, it is effective to use the public charging infrastructure at shopping areas to reduce the fuel consumption. However the fuel consumption reduction effect is improved only 0.2% by charging at these 4 additional locations compared to the 78% reduction effect by charging at home and work. This means that charging at home or at work already effectively covers daily driving area. Even if the number of charging facilities increases, the fuel reduction effect is saturated.

4.8 Charging of mass production PHEV in Japan

To investigate the usage frequency of public charging facilities, we studied travel and parking activity of the Prius Plug-in Hybrid in Japan.

Figure 20 shows the result from Aichi prefecture, Japan. The clock symbol shows the location of shopping areas where charging facilities are installed. The pie charts show the number of charges against the total number of parks at each shopping area.

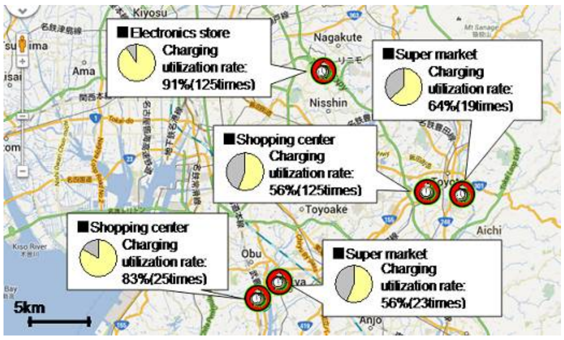


Figure 20. Charging of mass production Prius PHEV in Japan

Table 2 shows the outline of the analysis in Figure 20.

Table 2: Outline of the analysis of Figure 19

Number of vehicle	597
Number of trips	138,084
Measurement period	1.2 year

In these shopping areas, 56 to 91% of the PHEV's were actually charged when the vehicles were parked at these locations.
It was confirmed that the charging utilization rate was high when users visited commercial facilities like shopping areas with public charging availability.

5 SUMMARY

1) It has been confirmed that a fuel efficiency equivalent to the validation test in France is achievable in both the U.S. and Japan. Fuel reduction effect compared to gasoline vehicles is 49% in France, 50% in the U.S. and 56% in Japan.

2) In the validation test in France, the driver who charged the vehicle frequently achieved high fuel consumption reduction effect up to 69% compared to a gasoline vehicle with similar performance.

3) In order to improve the fuel reduction effect, the most preferable place to charge is at home or work.

4) It is preferable for fuel reduction to install charging facilities where vehicles are parked frequently for relatively longer periods such as shopping areas.

5) As a result from mass production PHEV's in Japan, it was confirmed that the charging utilization rate was high when users visited commercial facilities like shopping areas with public charging availability.

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