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Potential of Plug-in Hybrid Vehicle to Reduce CO_2 Emission Estimated from Probe Car Data in Japan

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Abstract

The reduction of CO_2 emission by the transport sector is necessary to be realized the low carbon society. In the near future, further CO_2 emission reduction is expected by the diffusion of PHEV. The aim of this study was to evaluate the potential of PHEV to reduce CO_2 emission based on real-world driving data (probe car data) and simulation. The probe car data of 35 conventional HEVs from April to August in 2011 were analyzed. The type of simulated PHEV system was all electric range, which operated only by battery power as long as available battery capacity was remaining (EV mode) , and then operated like conventional HEV after battery was depleted (HEV mode). Charging frequency was once a day at home after midnight as a realistic scenario. The results showed that the travel distance of 43% was converted to EV mode, and the gasoline consumption was reduced by 44%. The CO_2 emission was totally reduced by 17% considering electric power consumption. CO_2 emissions of each vehicle were reduced by 1-44%. CO_2 reduction amount of each vehicle varied widely reflecting their each own ways of car use and operating conditions. It is indicated that the diffusion of PHEV is a realistic and efficient measure to reduce CO_2 emissions in consideration of actual car use and operating conditions. Furthermore, low carbon power supply as well as diffusion of PHEV is more effective to CO_2 reduction.

Keywords: PHEV, simulation, energy consumption, environment, emissions

1 Introduction

The reduction of CO_2 emission by the transport sector is necessary to be realized the low carbon society. Especially, in Japanese local cities where there are many persons who depend on passenger cars for their daily transportation, it seems that the diffusion of conventional and plug-in hybrid electric vehicle (HEV and PHEV) is one of the most realistic and efficient measure to reduce CO_2 emission from passenger cars. HEV had already good fuel economy in the real world. PHEV is operated without fear of getting stranded due to battery depletion. In the near future, further CO_2 emission reduction is expected by the diffusion of PHEV.

However, there are problems to evaluate the CO_2 reduction effect of PHEV accurately. A variety of car use and operating conditions makes evaluation difficult. Mitsutani et al. [1] reported that the actual EV driving range of PHEV was decreased by the use of auxiliary electric power which is mainly consumed by cabin heating and cooling.

The aim of this study was to solve the following issues and evaluate the potential of PHEV compared with HEV to reduce CO_2 emission based on real-world driving data (probe car data) and modeling.

- Accurate estimation of the travel distance converted to EV mode, and the fuel consumption (CO_2 emission) in HEV mode according to actual car use and operating conditions.
- Consideration of CO_2 emission from electric power consumption by use of auxiliary: headlamp, air conditioner in summer.

2 Data collection

The probe car data of 35 conventional HEVs were collected in Toyota city, Japan. The social trial experiment starts in March 2011. In this paper, the data from April to August were used. The type of HEV was all the same. The data of second by second driving speed, fuel consumption, signal of headlamp use etc. were logged by on-board devices.

2.1 Data Properties

Fig.1 shows the frequency of the fuel economies. The fuel economies had wide distributions varied form 17.7 to 27.3 km/l. This type of HEV already had good fuel economies in the real world.

Fig.2 shows the daily using frequency for 35 vehicles. 27 vehicles were used over five days per week (over 71.4 % of daily using frequency). High daily using frequency is one of the properties of passenger car use in Japanese local cities.

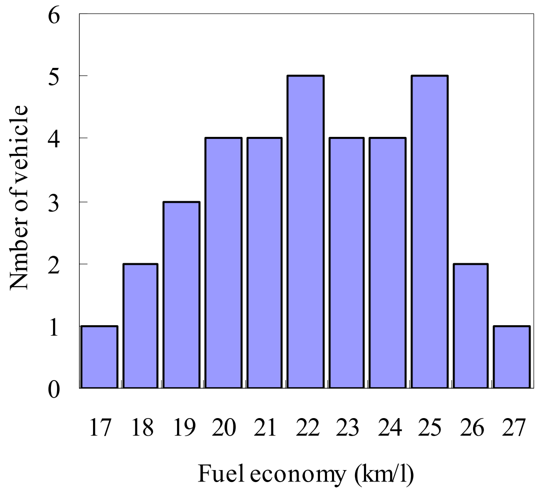

Figure1: Histogram of conventional HEV’s fuel economies in the real world (n=35)

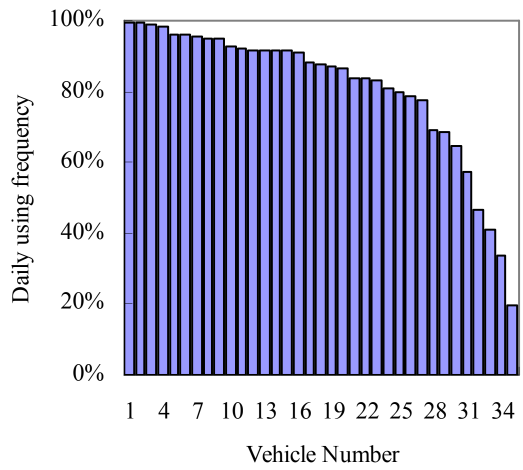

Figure2: Daily using (n=35)

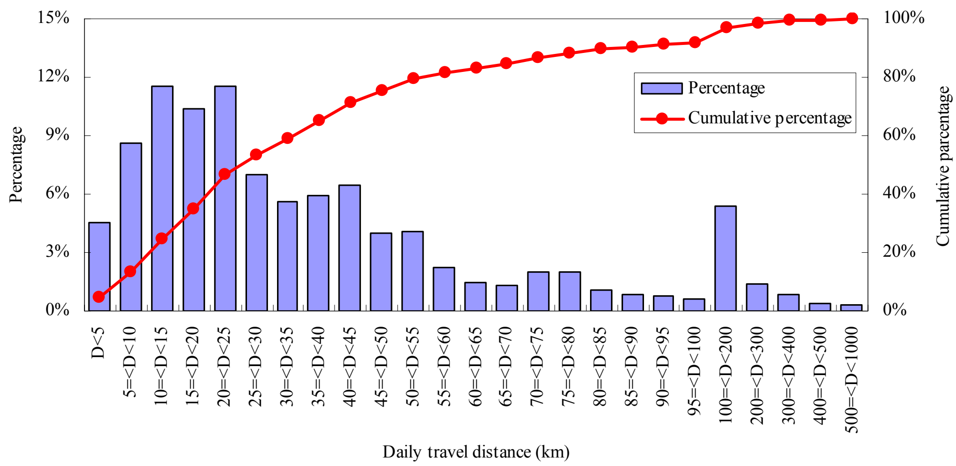

Figure3: Distribution of daily travel distance for 35 vehicles

Fig.3 shows distribution of daily travel distance for all 35 vehicles. Daily travel distance is an important property for PHEV to affect CO_2 reduction potential. About 50% of daily travel was less than 25 km. And about 90% of daily travel was less than 100 km. the longest daily travel distance was 980 km.

3 Simulation method

3.1 Simulation Outline

The inputs of the simulation model were PHEV specifications and probe car data of date, time, speed, fuel consumption rate and signal of headlamp use. The outputs of the simulation model were travel distance and electric energy consumption in EV mode, and travel distance and fuel consumption in HEV mode per one charge. Charging frequency was once a day at home after midnight as a realistic scenario.

3.2 Type of simulated PHEV

The type of simulated PHEV system was all electric range, which operated only by battery power as long as available battery capacity was remaining (EV mode) , and then operated like conventional HEV after battery was depleted (HEV mode) . It was assumed that the available battery capacity was 3.56kWh, vehicle weight was 1,430kg (120kg heavier than HEV). The other specifications were same as HEV: rolling resistance coefficient, air resistance coefficient and fuel consumption rate in HEV mode.

3.3 Electric power consumption in EV mode

The power $P(t)$ [W] consumed to propel a vehicle was calculated from both the vehicle specifications and the second-by-second speed pattern data using formulas (1) through (5) (KONDO et al. [2]).

$$P(t) = R(t) \cdot V(t) \tag{1}$$

where $R(t)$ is running resistance [N] and $V(t)$ is vehicle speed [m/s].

$$R(t) = R_r + R_l(t) + R_a(t) \tag{2}$$

where R_r is rolling frictional resistance, $R_l(t)$ is air resistance, $R_a(t)$ is acceleration resistance. Due to lack of road inclination data, hill climbing resistance is taken no account.

$$R_r = \mu \cdot M \cdot g \tag{3}$$

$$R_l(t) = \rho \cdot C_d \cdot S \cdot V(t)^2 / 2 \tag{4}$$

$$R_a(t) = (M + \delta \cdot M) \cdot \alpha(t) \tag{5}$$

where μ is the coefficient of friction [-], M is vehicle mass [kg], g is the gravitational constant [9.8 m/s^2], ρ is air density [kg/m^3], C_d is the coefficient of air resistance [-], S is projection area [m^2], δM is equivalent mass of rotating parts [kg] and $\alpha(t)$ is acceleration [m/s^2].

The running energy $E_{running}$ [Wh], regenerated energy $E_{regene.}$ [Wh] and energy used for auxiliary $E_{aux.}$ [Wh] were calculated using formulas (6) through (8). Operation in EV mode was continued while available battery capacity $E_{batt.capa.}$ was remaining as formula (9).

$$E_{running} = 1/\eta_1 \cdot \sum_{t=0, P>0}^{T_{EV}} P(t) \tag{6}$$

$$E_{regene.} = \eta_2 \cdot \sum_{t=0, P<0}^{T_{EV}} P(t) \tag{7}$$

$$E_{aux.} = \sum_{t=0, SignalON}^{T_{EV}} P_{headlamp} + \sum_{t=0, Jun.-Aug.}^{T_{EV}} P_{aircon.} \tag{8}$$

$$E_{batt.capa.} \geq E_{running} + E_{regene.} + E_{aux.} \tag{9}$$

where T_{EV} is travel time in EV mode [h], η_1 and η_2 are efficiency coefficient [-], $P_{headlamp}$ is power consumption of headlamp [W] and $P_{aircon.}$ is power consumption of air-conditioner [W].

η_1 and η_2 were adjusted that travel distance in EV mode was about 25 km in JC08 driving test pattern. $P_{headlamp}$ and $P_{aircon.}$ were assumed 160 W and 240 W, respectively.

3.4 Gasoline consumption in HEV mode

Studies aimed for estimation of HEV fuel consumption by modeling were reported (Anant et al. [3], WADA et al. [4] etc.). However, it seems that there are some difficulties with estimation in various speed patterns. In this study, fuel consumption FC [$cc_{\text{-gasoline}}$] in HEV mode was estimated by integrating real-world fuel consumption rate $R_{FC}(t)$ [$cc_{\text{-gasoline}}$/h] of the HEV's probe data as formula (10).

$$FC = \sum_{t=T_{EV}}^{T_{daily}} R_{FC}(t) + EX_{cold} \tag{10}$$

where T_{daily} is daily travel time [h], EX_{cold} is cold start excess of fuel consumption [$cc_{-gasoline}$]. EX_{cold} was estimated in consideration of engine start temperature, and added only after the end of EV mode.

3.5 Estimation of CO_2 emission

CO_2 emission EM_{CO2} of simulated PHEV [g_{-CO2}] was calculated using formula (11).

$$EM_{CO2} = (E_{running} + E_{regene.} + E_{aux.}) \cdot C_{elec.} + FC \cdot C_{gasoline} \quad (11)$$

where $C_{elec.}$ is the coefficient of CO_2 emission rate derived from commercial power consumption [g_{-CO2}/Wh] and $C_{gasoline}$ is the coefficient of CO_2 emission rate derived from gasoline consumption [$g_{-CO2}/cc_{-gasoline}$].
The coefficient C_{elec} of 0.417 g_{-CO2}/Wh was basically used, that was the latest coefficient of commercial power supply in Toyota City. The coefficient $C_{gasoline}$ of 2.32 $g_{-CO2}/cc_{-gasoline}$ was used.

4 Results and discussion

4.1 Total CO_2 reduction

Table1 shows the estimated result of PHEV compared to conventional HEV (original probe car data). The total travel distance of 35 vehicles for 5 months was 197 826km. the travel distance of 43% was converted to EV mode, and the gasoline consumption was reduced by 44%. On the other hand, commercial electric power of 12 567kWh was consumed additionally. In consideration of the CO_2 emission derived form electric power consumption, the CO_2 emission was totally reduced by 17%.

4.2 Effect of electric CO_2 emission rate

In this study, the coefficient of CO_2 emission rate derived from power consumption $C_{elec.}$ of 0.417 g_{-CO2}/Wh was basically used. However, the coefficient $C_{elec.}$ could vary in the future depending on generating capacity by energy source. Thus, the effect of the coefficient $C_{elec.}$ on CO_2 reduction was also examined. Fig.4 shows the relationship between CO_2 emission rate derived from power consumption $C_{elec.}$ and CO_2 reduction rate of PHEV compared to conventional HEV. Because conventional HEV already had good fuel economy, CO_2 reduction rate became below 0% at coefficient $C_{elec.}$ greater than 0.7g_{-CO2}/Wh. It is indicated that low carbon power supply as well as diffusion of PHEV is necessary for effective CO_2 reduction.

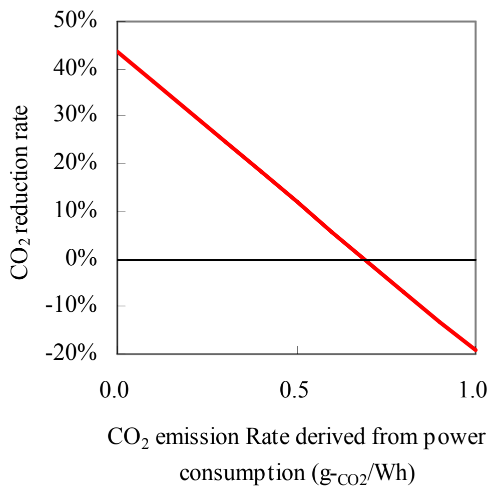

Figure4: Relationship between CO_2 emission rate derived from power consumption and CO_2 reduction rate of PHEV compared to conventional HEV

Table1: Overview of estimated result (35 vehicles for 5 months)

	Conventional HEV	Estimated PHEV (EV mode) (HEV mode)
Travel distance [km]	197826	197826 (85034) (112792)
Gasoline consumption [L]	8608	4858 (-) (4858)
Comercial power consumption [kWh]	(-)	12567 (12567) (-)
CO_2 emission [kg]	19971	16511 (5241) (11271)

4.3 CO_2 reduction of each vehicle

CO_2 reduction of each vehicle for five months (April through August) also discussed. Fig.5 shows the relationship between travel distance and CO_2 reduction rate, and Fig.6 shows the relationship between travel distance and CO_2 reduction amount of PHEV compared to conventional HEV for 35 vehicles.

The CO_2 emissions of each vehicle were reduced by 1-44% with a wide range of CO_2 reduction rate. The longer travel distances, the lower were CO_2 reduction rates. However, CO_2 reduction amount of each vehicle varied widely and even if CO_2 reduction rates were high, CO_2 reduction amounts are not large. It seems that they reflected their each own ways of car use and operating conditions.

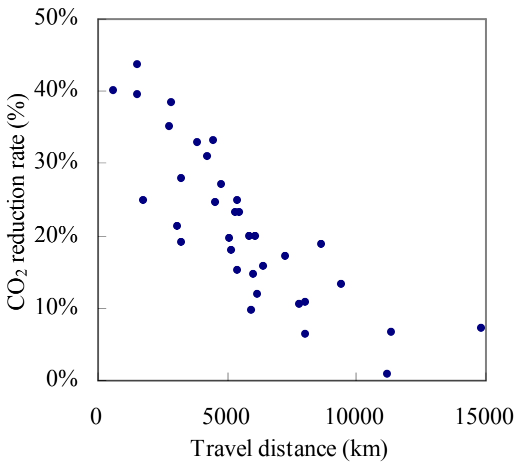

Figure5: Relationship between travel distance and CO_2 reduction rate of PHEV compared to conventional HEV (n=35)

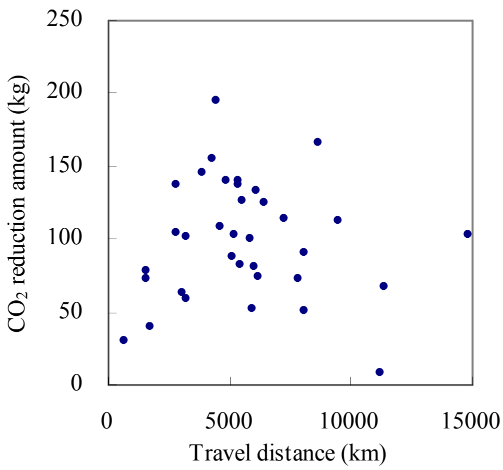

Figure6: Relationship between travel distance and CO_2 reduction amount of PHEV compared to conventional HEV (n=35)

4.4 Effect of auxiliary use

The electric energy consumption by use of auxiliary: headlamp and air conditioner was estimated. Fig.7 shows the distribution of electric energy consumption in EV mode for three months in summer (June through August). The distribution of air conditioner and headlamp were 6.8% and 0.4%, respectively. This means that by use of auxiliary electric power in summer, travel distance in EV mode decreased by 7.2%. The effect of cabin heating remains to be evaluated.

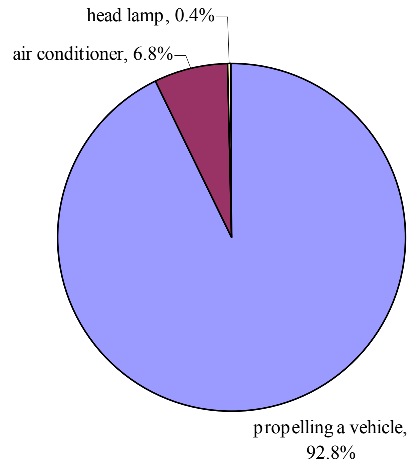

Figure7: Distribution of electric energy consumption in EV mode in summer, June through August

5 Conclusion

The potential of PHEV to reduce CO_2 emission compared with conventional HEV was evaluated based on real-world driving data (probe car data) and simulation. The probe car data of 35 conventional HEVs from April to August were analyzed. The type of simulated PHEV system was all electric range, which operated only by battery power as long as available battery capacity was remaining (EV mode) , and then operated like conventional HEV after battery was depleted (HEV mode). Charging frequency was once a day at home after midnight as a realistic scenario.

Results showed that:

- The travel distance of 43% was converted to EV mode, and the gasoline consumption was reduced by 44%.
- The CO_2 emission was totally reduced by 17% considering electric power consumption.
- CO_2 emissions increased at the coefficient (CO_2 emission rate derived from power consumption) greater than $0.7g_{-CO2}$/Wh.
- CO_2 emissions of each vehicle were reduced by 1-44%. The longer travel distances, the lower

were CO_2 reduction rates. However, CO_2 reduction amount of each vehicle varied widely reflecting their each own ways of car use and operating conditions.

- The travel distance in EV mode decreased by 7.2% by use of auxiliary electric power in summer.

It is indicated that the diffusion of PHEV is a realistic and efficient measure to reduce CO_2 emissions in consideration of actual car use and operating conditions. Furthermore, low carbon power supply as well as diffusion of PHEV is more effective to CO_2 reduction.

The effect of cabin heating remains to be evaluated.

Acknowledgments

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References

[1] N. Mitsutani, M. Yamamoto, T. Takaoka, *Development of the plug-in hybrid vehicle, THS-II PLUG-IN*, Proceedings of the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, CD-ROM(2010)

[2] Y. Kondo, H. Kato, K. Matsuhashi, *Evaluation of electric vehicles based on long-term travel activity data of passenger cars,* Proceedings of the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, CD-ROM(2010)

[3] Anant D. Vyas, Danilo J. Santini, Larry R. Johnson, *Potential of plug-in hybrid electric vehicles to reduce petroleum use, issues involved in developing reliable estimates,* Transportation Research Record, 2139(2009), 55-63

[4] Y. Wada, S. Shimada, W. Jibin, Y. Kamiya, Y. Daisho, K. Morita, *Environmental performance evaluation of plug-in hybrid electric vehicles,* World Electric Vehicle Journal, ISSN 2032-6653, Vol.3(2009)

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