RIETI Discussion Paper Series 12-E-035

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RIETI Discussion Paper Series 12-E-035
May 2012

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Abstract

The future of both the automobile and the transportation industries has been of significant interest to many people. In this study, we investigate the economic validity of the diffusion of fuel cell vehicles (FCVs) and all-electric vehicles (EVs), comparing the benefit and cost for diffusion of alternative vehicles by employing cost-benefit analysis. We assume the amount of CO_2 and NOx emissions and gasoline use reduction as a benefit, by switching from internal combustion engine (ICE) vehicles to alternative vehicles; and the purchase amount, infrastructure expenses, and maintenance of alternative vehicles as a cost. We obtained data from two alternative fuel vehicles from an interview with an automobile maker in Japan. Considering uncertainties, we conducted a sensitivity analysis of the cost-benefit ratios. The scenarios used are the following: the progress of alternative vehicle production, the increase in CO_2 abatement cost, the increase in the price of gasoline, and the target year for diffusion. In summary, the results show that the diffusion of FCVs will not be economically feasible until 2110, even if their purchase cost is decreased to that of an ICE vehicle. The diffusion of EVs might be possible by 2060 depending on the increase in gasoline prices and the CO_2 abatement costs.

Keywords: Alternative fuel vehicles; Cost benefit analysis

JEL classification: O30, Q59

1. Introduction

Climate change is one of the most serious challenges of the 21st century. To avoid dangerous climate change, a variety of greenhouse gas (GHG) mitigation actions must be taken in all sectors of the global energy system. The International Energy Agency (IEA) indicated that the road transport sector accounted for approximately 17% of energy-related CO_2 emissions in 2007 and is likely to have a higher share in the future unless strong action is taken (IEA, 2009). Furthermore, if a 50% decrease in 2005 energy-related CO_2 emissions are to be achieved by 2050, the transport sector will be required to make a significant contribution. However, we need to acknowledge that transport's large economic role and its significant influence on daily life will make the required rapid changes more difficult to achieve (IEA, 2000, 2008).

It is therefore critically important to develop a long-term, cost-effective strategy for reducing CO_2 emissions from the transport sector. In the past, the Japanese government implemented several environmental policies to move from gasoline-fueled vehicles to more efficient vehicles, such as hybrid and plug-in hybrid vehicles. As a result, the number of these alternative, efficient vehicles production is increasing.

In addition, the Japanese government currently claims that two million all-electric vehicles (EVs) and five million hydrogen fuel cell vehicles (FCVs) will be on the road in Japan before 2020.

These two types of alternative vehicles do not produce emissions; therefore, EVs and FCVs, alternatives to conventional vehicles based on the internal combustion engines (ICEs), have the potential to greatly reduce the emissions generated by the transport sector. In fact, the i-MiEV, produced by Mitsubishi Motors, was already launched for fleet customers in Japan starting in July 2009 and for the wider public in April, 2010. In addition, the national government is offering subsidies for EVs, and several local governments are also offering additional subsidies that could reduce the price of EVs. The main objective of these policies is to provide incentives to early adopters and to speed the implementation of pilot programs for verifying EV and FCV technology developments.

However, no previous study has determined when these new technologies will become economically and technologically feasible by considering future energy prices, carbon prices and technological progress. The targets for the number of EVs and FCVs were not provided by previous studies because of the EV and FCV characteristics, such as short mileages per battery charge, high production cost and high purchase price. Although car sharing services and rent-a-car businesses were introduced to resolve these issues, the targeted user's lifestyle and transport patterns were not matched with those services.

In our paper, we analyze whether the large scale use of FCVs and EVs in Japan is justified from an economic perspective, and if so, under what conditions. The validity of the diffusion of alternative vehicles has been discussed in earlier studies. Many of the studies are divided into two approaches (see Paolo, 2007). In the first approach, researchers focus on hydrogen or electric supply. Given a particular infrastructure for production and distribution, this type of study assesses the hydrogen or electric applications, for example, by analyzing how many FCVs or EVs can be supported (Ford Motor Company, 1997, Simbeck and Chang, 2002, Albertuset al., 2008, Fischer, Werber, and Schwartz, 2009). In the second approach, researchers determine the hydrogen or electric demand needed after assuming the number of FCVs or EVs on the road, the distance travelled and the fuel efficiency of the vehicles. Given the demand for hydrogen or electricity and the technologies used in the production, storage, transportation, and dispensing of the fuel, authors can determine a number of parameters that describe the hydrogen or electric system (McKinsey, 2010, Jonathan et al., 2011). Learning curves and economies of scale are sometimes considered, for example, in the California Hydrogen Highway Network (CHHN) (2005), Gielen and Simbolotti (2005), Martinus et al. (2005), and HyWays (2006).

We adopt the second approach to examine the benefit and costs of the diffusion of FCVs and EVs and their effect on both GHG emissions and the infrastructure needed for the generation and distribution of the fuel. As Paolo (2007) noted, much more analysis examining the comprehensive factors affecting the diffusion of alternative vehicles is needed. In our study, we conduct a sensitivity analysis considering cost reduction in FCV and EV production, abatement cost of CO_2, and gasoline prices. In addition, we use data obtained from national reports on the two alternative vehicle types and interviews with automobile makers in Japan. By examining alternative vehicle diffusion more realistically, this study could contribute to environmental research, development and policy making in the transportation sector. Section 2 outlines the structure of the cost-benefit analysis, sensitivity analysis and key assumptions in our scenario. The data we used are represented in Section 3. We discuss the result of the scenarios in Section4. Lastly, we conclude our study in Section 5.

2. Method

2-1. Cost-benefit analysis

We employ a cost-benefit analysis (CBA) to evaluate the validity of FCV and EV diffusion. CBA is useful for determining the feasibility of a project from an economic standpoint. In our study, we use the benefit/cost ratio (B/C) as a validity indicator for diffusion. The B/C is calculated from variables shown in Table 1. It is important to keep in mind the effect to other industry such as electricity industry by the change of energy supply (e.g., reduction in nuclear energy) needs not be accounted because the analysis needs the investigation requires only the effects on the targeted industry.

2-1-1. Benefit

We consider reductions in CO_2 and NOx emissions and a reduction in gasoline use as benefits that result from replacing ICE vehicles with alternative vehicles. The benefit of replacing an ICE vehicle with an alternative vehicle *m* (i.e., FCVs or EVs) in year *t* is calculated as follows:

$$B_{t,m} = \sum_{p} ER_{t,p,m} \times price_{t,p} \tag{1}$$

ER indicates the amount of reduction in the emissions of CO_2, NOx, and gasoline use. In the case of CO_2 and NOx, *price* represents the marginal abatement cost. In the case of gasoline, *price* indicates the price of gasoline per liter. Therefore, the benefit $B_{t,m}$ is represented as the sum of each *ER* multiplied by the reducing cost in each material *p* (i.e., CO_2, NOx, and gasoline).

The amount of reduction in each material *m* in year *t* is represented in Eq.(2).

$$ER_{t,p,m} = NAV_{t,m} \times (E_{p,ice} - E_{p,m}) \times TD \tag{2}$$

The net number of alternative vehicles (*NAV*) indicates the number of ICE vehicles replaced by alternative vehicles from2011 until *t*, i.e., the number of alternative vehicles used in year *t*. $E_{p,ice}$ and $E_{p,m}$ represent the amount of emissions *p* per kilometer for ICE vehicle *ice* and alternative vehicle *m*, respectively. *TD* represents the annual distance traveled per year.

Therefore, the total benefit (*TB*) is calculated by the sum of these each factor components, i.e., the reduction in CO_2, NOx, and gasoline. The discounted present value of the benefit is then calculated and evaluated at 2011 prices. *TB* of type *m* alternative vehicle is defined as follows.

$$TB_m = \sum_{t=2011}^{T} \exp\{-i \times (t-2011)\} \times B_{t,m} \tag{3}$$

In Eq.(3), *T* shows the target year for the diffusion of five million alternative vehicles and *I* indicates a discount rate of 4%. The reason for five million being the diffusion target is explained in 2-1-3 section.

2-1-2. Cost

The cost of replacing ICE vehicles with alternative vehicle *m* (i.e., FCVs or EVs) in year *t* is calculated as follows.

$$C_{t,m} = C_{t,m,\inf rastructure} + C_{t,m,vehicle} \tag{4}$$

Cost, $C_{t,m}$, is divided into two factors. $C_{t,m,\inf rastructure}$ consists of the construction and operating cost of the infrastructure needed for alternative vehicle diffusion. $C_{t,vehicle}$ indicates the differences between the sum of the purchase and running cost of an alternative vehicle *m* compared to an ICE vehicle and it is estimated in Eq.(5).

$$C_{t,m,vehicle} = (C_{t,m,prodution} - C_{t,ice,prodution}) + (C_{t,m,running} - C_{t,ice,running}) \tag{5}$$

Therefore, the total cost (*TC*) is calculated based on the sum of the each cost and is discounted to arrive at a present value of the cost evaluated at 2011 prices. *TC* of type *m* alternative vehicle is defined as follows.

$$TC_m = \sum_{t=2011}^{T} \exp\{-i \times (t-2011)\} \times C_{t,m} \tag{6}$$

From Eq.(3) and Eq.(4), we can estimate the B/C as follows:

$$B / C_m = TB_m / TC_m \tag{7}$$

2-1-3. Key Assumption

As we discussed above, we assume that the total cost, i.e., *TC* in Eq.(6) is the sum of the differences between purchase cost and running cost of alternative vehicles versus those of ICE vehicles and the construction and operating costs of the needed infrastructure. On the other hand, we consider the sum of expected reduction of CO_2, NOx emissions and gasoline use from replacing ICE vehicles with alternative vehicles as the total benefit, i.e., *TB* in Eq.(3). We estimate the B/C of each case of alternative vehicle diffusion (FCVs or EVs).

We assume that the target years for the diffusion of five million FCVs (EVs) are set from 2011 to 2020, 2060, or 2110 and we refer to those target years as the *Short, Middle*, and *Long target*. In our calculation, we assume that the number of replacement ICE vehicle to FCVs (or EVs) is constant over time. Therefore, the numbers of replacement vehicles per year are different for each target year. This implies that if the target year is 2060, the number of replacement vehicles is 100,000 per year. The replacement number per year is 500,000 for the 2020 case and 50,000 per year in the case of a 2110 target date. The closer the target year, the more alternative vehicles are produced per year.

In the FCV distribution scenario, we assume that hydrogen is made in a hydrogen purification plant (HPP) by the electrolysis of water using the electricity generated by a nuclear plant. Nuclear-generated electricity does not pollute the atmosphere with greenhouse gas emissions like a thermal electric power plant. Renewable energy-generated electricity, such as wind power, and solar power, cannot generate enough electricity to provide the amount of hydrogen needed to refuel FCVs. The hydrogen produced in HPP is transported by hydrogen transport trucks from HPPs to hydrogen refueling stations (HSTs) where users can refuel their FCVs. The number of trucks is calculated using the number of HSTs and the distance from the nearest HPP.

We assume that the FCVs are distributed in each prefecture according to the proportion of the number of gas stations in each prefecture and the number of HSTs. The capacity of HPP is determined by the demand for hydrogen in the last usable year of the HPP, i.e., if the number of usable years is t, the capacity is defined based on the hydrogen demand after t-1 years.

In the case of EVs, the driver can recharge the battery in a recharging station (RST) using a fast charger. The number of fast chargers is one per charging station. The number of fast chargers needed is estimated by calculating the battery recharging time, mileage per charge, annual vehicle mileage, and the number of distributed EVs in each year. We assume that the annual mileage of alternative vehicles is the same as ICE vehicle based on interview results. The number of trucks needed is calculated using the number of HSTs and distance from the nearest HPP.

Furthermore, analysis does not incorporate future changes in urban characteristics such as introduction of compact city and smart building utilizing potentially EV recharging connected to the building. If the EV provides additional energy saving which merit to our benefit estimate, this can be included in our estimate but giving high cost of the system for building and city infrastructure, the effect might be small. We do not provide the results here for this sensitivity analysis but simple changes in additional merit of EV as coefficient do not change the results much.

2-2. Sensitivity analysis

In this study, we consider the following three sensitivity factors that might significantly affect the benefit/cost ratio.

2-2-1. Sensitivity to technology

The first factor is sensitivity to technological progress. We consider the cost reduction of EV batteries and FCV production using the exogenous technical progress ratio by learning curve. Learning curve (or experimental curve) is a microscope model describing the human activity of accumulating knowledge or experience by cumulative production and is usually adapted to an industrial production process. The typical learning curve is described as follows:

$$Y_i = AX_i^{-r} \quad (8)$$

where the X_i is the cumulative number of products at ith production, Y_i product cost at ith production, and A is constant.

As the number r in the exponent is not easy to understand, a simpler expression is introduced as a progress ratio: ($F = 2^{-r}$). F shows how the production cost could be reduced each time cumulative production is doubled. When F is 90%, it implies that the cost is reduced to 90% each time the cumulative production volume is doubled. In this paper, we applied the progress ratio exogenously to calculate the production cost of FCV and EV batteries for considering cost reduction due to the cumulative production[1].

We show the relationship between cumulative production and purchase cost of FCVs and EVs in Fig. 1 and Fig. 2, respectively, where three types of progress ratios are considered. The *Lower progress* scenario implies that the cost reduction due to cumulative production is the smallest in all scenarios. In other words, the production costs of FCVs and EVs are the highest among the three scenarios. The purchase costs of the five millionth FCV and EV are approximately \$90,000 and \$39,000, respectively. The cost decreases by approximately \$132,000 and \$12,000 from the initial FCV and EV purchase costs, respectively. The *Realistic* scenario indicates that the purchase cost of the five millionth FCV and EV converges to the target value of the automobile

[1] If we had historical cost data, we could estimate the progress ratio F by regression analysis. However, there is no previous research estimating the F of FCV production cost and EV battery cost.

company we interviewed, which is approximately \$56,000 and \$31,000 per unit, respectively. The last scenario is the *Higher progress* scenario, in which the five millionth purchase cost of FCV and EV decreases to \$21,000 per unit.

The progress ratio we applied in the *Lower progress*, *Realistic* progress, and *Higher progress* scenarios are 0.96, 0.94, and 0.90, respectively, for the FCV diffusion scenario and 0.98, 0.96, and 0.92, respectively, in the case of the EV diffusion scenario.

2-2-2. Sensitivity to the marginal abatement cost of CO_2

The second sensitivity analysis focused on the marginal abatement cost of CO_2. There is no certainty about future CO_2 prices. Therefore, we assume three CO_2 price scenarios for simplicity (see Fig.3). The first scenario maintains the current European Union Emission Trading Scheme (EU-ETS) CO_2 emissions price. The second scenario is *Optimistic* and the third one is *Pessimistic*. In the *Optimistic* scenario, the abatement cost of CO_2 increases approximately linearly (see Cline, 2004). The *Pessimistic* scenario assumes that the abatement cost of CO_2 increases exponentially (see Manne, 2004).

2-2-3. Sensitivity to the gasoline price

The third sensitivity factor is the gasoline price. In our model, the gasoline price is an important factor. Similar to the CO_2 price, we do not model the gasoline price using past data. Instead, we assume three gasoline price scenarios following the international oil price assumptions reported by IEA (2010). These three scenarios are provided in Fig.4. The first scenario is the *450ppm* scenario. The *450ppm* scenario sets out an energy pathway that is consistent with the goal of limiting the increase in average temperature to two degrees. This scenario shows the oil price remaining steady at $90 per barrel. Note that this is the oil price scenario and it is independent from carbon price scenario. The second scenario is the *Current* policy scenario. The *Current* policy takes into consideration only those policies that have been formally adopted by mid-2010. In this case, the price of oil increases to approximately $130 per barrel by 2035. The last scenario is the *New* policy scenario. This scenario assumes cautious implementation of recently announced commitments and plans, even if not yet formally adopted. The oil price in this scenario increases to approximately $120 per barrel by 2035.

3. Data

We obtained specifications for the FCV, EV, ICE vehicles, and recharging station for EV users from interviews with one of the largest automobile manufacturing companies in Japan. These data are described in Table 2. The fuel consumption of FCVs is modeled as 13.6km/Nm^3.The EV battery is modeled as a 10 km/kWh battery system with a 160 km range. We model that standard

ICE vehicle as 15.5 km/l. The specifications for the HPP, HST, and hydrogen transport trucks are obtained from NEDO (2007)[2]. For the NOx reduction benefit, we use estimates from the European Union (NETCEN, 2002), which report the marginal external cost of NOx in 15 EU countries because there is no equivalent study in Japan. Considering the high population density in Japan, the mean of the 15 EU countries is used as the lower bound of the estimates and the highest value is used as the upper bound. A discount rate of 4% is used to calculate the present value of both the benefit and the cost.

4. Results and discussion

Tables 3 and 4 show the B/C ratio result for the five million FCVs and EVs diffusion scenario[3]. The first column shows the three cost reduction scenarios, i.e., *Lower progress*, *Realistic progress*, and *Higher progress* of FCV (or EV) production. The second column shows the target year for the diffusion of five million FCVs (EVs). The first row is divided into three scenarios for gasoline price. As we discussed above, those three scenarios (*Current* policy scenario, *New policy* scenario, and *450ppm* scenario) differ in the rate of oil price increase. The second row shows the

[2] We summarize the assumption of HST, HPP, RST, and number of trucks needed in the Appendix. These data are provided in Table A-1 to A-3 in the Appendix.

[3] The result of each cost and benefit of FCV and EV are described in Table A-4 to A-7 in the Appendix.

three abatement cost of CO_2 reduction scenarios. The abatement cost of CO_2 increases differently depending on the scenario (*Pessimistic* scenario, *Optimistic* scenario, and *Constant* scenario).

4-1. FCV diffusion scenario

We do not find economic viability for FCV diffusion under any scenario, i.e., the benefit is lower than cost for FCV diffusion in each scenario. The highest B/C is 0.79 for *Long target* in the *Current* policy gasoline price and *Higher progress* scenario. On the other hand, the lowest B/C is 0.05 for the *Short target* under the *New* policy and *450ppm* gasoline price scenario. The highest B/C scenario is 16 times higher than the lowest B/C scenario. Based on the CO_2 abatement cost scenario, the *Pessimistic* scenario has the highest B/C, and the *Optimistic* scenario has the second highest. In the case of the gasoline price scenario, the *Current* policy scenario B/C is the highest, and the second highest is the *New policy* scenario. For each scenario, the goal of FCV diffusion is better in terms of B/C for the longer target.

Fig. 5 shows the proportion of cost factor under the *450ppm* oil price scenario. This proportion is how much each single factor accounts for the total cost after discounting in each scenario. We divided the total cost into seven factors, i.e., the purchase cost of FCV and ICE vehicles, the cost for hydrogen production (the construction and running cost of the HPP), the construction and running cost of HST, the transportation cost of hydrogen which consist of the production and running costs of trucks and the expense of hydrogen transportation from the HPP to HST, and the cost of gasoline and hydrogen used by passengers. In addition, because the increase in CO_2 abatement cost does not influence the cost factors, we do not describe the CO_2 abatement cost scenarios in this figure.

Our results indicate that the purchase cost of FCVs is the highest cost in all scenarios. The proportion of FCVs in the *Lower progress* scenario for the *Short target* is approximately 80% and approximately 75% in the *Middle* and *Long targets*. For the *Lower progress* ratio, it is approximately 50% for the *Short target* and 40% for the *Middle* and *Long targets* in the *Higher progress* scenario. Because of the high production cost for the FCVs, they require a technological breakthrough in production. Therefore, government support for R&D and fundamental research to reduce the cost of the main parts of FCVs are essential.

Comparing the CO_2 abatement cost scenario and the gasoline price scenario, the effect of the gasoline cost scenario on B/C is larger in the *Short* and *Middle target cases*. In the *Long target* case, the effect of the CO_2 abatement cost on B/C is larger compared to the gasoline price scenario. For instance, in the *Higher progress* scenario for the *Long target* case, the B/C under the *Constant* scenario is 0.48 and 0.25 in of the *Current* policy and *450ppm* scenario, respectively. The difference between the *Current* policy and *450ppm* scenario is 0.23. This result shows the effect of the gasoline price increase because the gasoline price under the *450ppm* scenario is constant, i.e., $1.38

per liter, and this price does not change until 2110. In the *450ppm* scenario, the difference between the *Pessimistic* scenario and the *Constant* scenario is 0.26 under the *Higher progress* scenario. Similar to gasoline price sensitivity, this difference represents the effect of an increasing CO_2 abatement cost. Comparing two sensitivity variables, the differences in the CO_2 abatement cost scenario between the *Pessimistic* and *Constant* scenario is higher than those in the gasoline price scenarios between the *Current* policy and *450ppm* case.

In the *Short target* case, the differences between the *Pessimistic* and *Constant* CO_2 abatement cost scenarios under the *450ppm* scenario are zero. Compared to each gasoline price scenario under the *Constant* CO_2 abatement cost scenario, the difference between the *Current* policy and the *450ppm* scenario is 0.09. Therefore, unlike in the *Long target* case, the effect of gasoline prices is higher than that of CO_2 abatement cost. We can see these trends in not only the *Higher progress* scenario but also in the *Lower* and *Realistic* scenarios. This is because the total benefit of CO_2 reduction is increasing faster than that of gasoline use reduction for the *Long target* case. For the *Short* and *Middle target* cases, the result is the opposite.

To explain these trends, we show the proportion of the benefit factor of FCV diffusion in the *450ppm* and *Current* policy gasoline price scenarios in Fig. 6. In the *Constant* CO_2 abatement cost scenarios under the *450ppm* scenario, the proportions of CO_2 emissions and gasoline use reduction are approximately 2.2% and 97.5% in both the *Long* and *Short target*s. In the case of the *Current* policy scenario, these factors are approximately 1.8% and 98% in both the *Long* and *Short target* cases. Therefore, the contributions to the benefit of each of these two factors are not very different between the two gasoline price scenarios. On the other hand, in the *Pessimistic* scenario under the *450ppm* scenario for the *Long target* case, the proportion of CO_2 emissions reduction increases to 52%, and gasoline use reduction decreases to 48%. Therefore, as we discussed above, the CO_2 emissions reduction cost is the more important factor for FCV diffusion, especially in the long term. Lastly, the amount of the benefit of NOx reduction effect is under 1% in all of the benefit factors under all scenarios.

4-2. EV diffusion scenario

In the EV diffusion scenarios, we find economically viable scenarios, especially for the *Long target*. For the *Short target*, the diffusion of EVs would be difficult under all scenarios. In the case of the *Middle target* date, diffusion may be possible if both the gasoline price and the abatement cost of CO_2 increase, and the purchase cost of EVs decreases to that of ICEs. For the *Long target*, if the gasoline price and CO_2 abatement cost increase, the diffusion of EVs would be economically viable even if their purchase cost is higher than the target price of the automobile maker we interviewed. In addition, the B/C for the *Long target* under the *Higher progress* scenario is economically desirable except for the *Optimistic* and *Constant* scenarios under the *450ppm* gasoline price scenario. The effect of each scenario on B/C considering the CO_2 abatement cost, gasoline price, and the target year is similar to the FCV diffusion scenario. That is, the B/C of EV diffusion is higher following the *Pessimistic*, *Optimistic*, and *Constant* scenarios when comparing each CO_2 abatement cost scenario. In the gasoline price scenario, the B/C is higher following the *Current* policy, *New policy*, and *450ppm* scenarios. Compared to the *Short*, *Middle*, and *Long target* cases, the B/C is higher following the *Long*, *Middle*, and *Short* scenarios. The highest B/C scenario is 2.78 and is approximately 13 times higher than that of the lowest scenario, 0.22.

As in Fig. 5, Fig. 7 shows the proportion of cost factors. We divide the total cost into five factors: the purchase cost of EVs, which is twice the sum of the production cost of EV batteries and the rest of EV productions; the purchase cost of ICE vehicles; the construction and operating cost of RST; the refueling cost of gasoline for ICE vehicles; and the recharging cost of EVs.

The EV purchase cost share is the highest proportion in all scenarios and is 71.7% on average. In addition, there is little change in this share among scenarios; for example, 76.9% and 68.6% are the highest and lowest shares, respectively. The contribution to the total cost of ICE vehicle production is higher in the *Lower progress* scenario compared to the *Higher progress* scenario, approximately 17% and 5% on average, respectively. The proportions of the EV charging station are approximately 0.4% and 0.8% in the *Lower* and *Higher progress* scenarios. Gasoline refueling cost accounts for 15.2% on average in all scenarios, 7.5 times higher than EV recharging cost on average. According to these results, EV purchase cost reduction has the most significant effect on the diffusion of EVs.

In Fig. 8, we show the proportion of benefit factors for EV diffusion under the *450ppm* and *Current* gasoline price scenarios. These results are similar to the FCV results. Except for the *Long target* date under the pessimistic scenario, the proportion of gasoline use reduction accounts for approximately 97.1% on average, and for CO_2 emissions reduction, it accounts for approximately 2.6% on average in both scenarios. On the other hand, the proportion of those two factors under the *Pessimistic* scenario is 73.3% and 26.4% on average for the *Long* and *Short target* scenarios. For the *Long target* case under the *Pessimistic* scenario, the proportion of gasoline use reduction is 44.3% and 56.5% in the *450ppm* scenario and *Current* policy scenario, respectively. The proportion of CO_2 emissions reduction is 55.5% and 43%, respectively. Therefore, as in the FCV case, the effect of CO_2 emissions reduction on B/C is significantly higher in the case of a CO_2 abatement cost increase. In addition, compared to the FCV case, the effect of a CO_2 emissions reduction is higher than that of a gasoline use reduction because the amount of CO_2 emissions of EVs in annual mileage is relatively lower than that of FCVs, i.e., 559 kg- CO_2 per year for an FCV and 425 kg- CO_2 per year for an EV. Lastly, as in the FCV case, the amount of the benefit of NOx reduction effect is under 1% in all of the benefit factors under all scenarios.

5. Conclusion

The future of both the automobile and the transportation system is of significant interest to a large audience. In this study, we investigate the economic validity for FCV and EV diffusion by employing cost-benefit analysis. We obtain the data of two alternative fuel vehicles from an interview with an automobile maker in Japan. Considering uncertainties, we applied a sensitivity analysis to the cost-benefit ratios. These scenarios consist of the following: progress in the speed of alternative vehicle production, the increase of CO_2 abatement cost, gasoline price increase, and the target year for the alternative vehicle diffusion.

In summary, the results show that the diffusion of FCVs is not economically feasible until 2110, even if their purchase cost is decreased to that of ICE vehicles. On the other hand, the diffusion of EVs might be possible as soon as 2060, considering the increase of gasoline price and the CO_2 abatement cost.

The major obstacle to the widespread use of FCVs is the high purchase (or production) cost of FCVs. Therefore, innovation is needed to produce a significant cost reduction in FCV production. In addition, the government must promote the development of such fundamental technological development. As in FCVs, the electric battery is one of the major obstacles to the diffusion of EVs. Major progress in technology is required to reduce the production costs and improve the performance of EVs. We believe that our work can serve as a framework to structure thinking about investment and policy for the diffusion of alternative fuel vehicles. In addition to this detailed industry specific analysis, understanding the effect of new technologies to other industries is also important to understand. Future work can utilize application of computational general equilibrium analysis which provides effect to other industries.

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Table 1 Benefit-Cost Factors

Benefit factors	・Emissions reduction of CO2 and NOx. ・Gasoline use reduction.
Cost factors	・The differences of production and running cost of FCV or EV and ICE vehicles. ・Construction and running cost of infrastructure for alternative vehicle diffusion.

Table 2 Characteristics of each vehicle type.

	Hydrogen fuel cell vehicle	Battery electric vehicle	Internal combustion engine vehicle
Purchase price (Thousand dollar)	222	51	22
Initial production cost (Thousand dollar)	111	25.5	11
Battery production cost (Thousand dollar)	-	20	-
Fuel consumption	13.6 km/ Nm^3	10km/kWh	15.5 km/l
Refueling/Recharging cost	1.1 $\$/Nm^3$	0.12 $/kWh	1.3$/l
CO2 emissions per fuel consumption	0.76kg-CO2/m^3	0.425kg-CO2/kWh	2.36kg-CO2/l
NOx emissions per mileage	0.00 g/km	0.00 g/km	0.05g/km
Lifetime	10year		
Discount rate	4%		
Running distance	10000 km/year		

Note: The values are based on our interviews to automobile company.

Table 3 The result of 5 million FCV diffusion scenario

Gasoline				*Current* policy scenario			*New* policy scenario			*450ppm* scenario		
CO2				*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*
Progress ratio	*Lower progress*	Target year	Short	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
			Middle	0.13	0.13	0.12	0.11	0.11	0.10	0.09	0.08	0.08
			Long	0.22	0.17	0.14	0.20	0.15	0.11	0.16	0.11	0.08
	Realistic Progress	Target year	Short	0.09	0.09	0.09	0.08	0.08	0.08	0.07	0.07	0.07
			Middle	0.20	0.19	0.18	0.17	0.16	0.15	0.13	0.13	0.11
			Long	0.34	0.26	0.21	0.30	0.22	0.17	0.25	0.17	0.12
	Higher progress	Target year	Short	0.20	0.20	0.19	0.18	0.17	0.17	0.16	0.16	0.16
			Middle	0.45	0.44	0.41	0.37	0.35	0.33	0.28	0.26	0.24
			Long	0.79	0.60	0.48	0.66	0.49	0.37	0.51	0.35	0.25

Table 4 The result of 5 million EV diffusion scenario

Gasoline				*Current* policy scenario			*New* policy scenario			*450ppm* scenario		
CO2				*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*	*Pessimistic*	*Optimistic*	*Constant*
Progress ratio	*Lower progress*	Target year	Short	0.28	0.28	0.28	0.25	0.25	0.25	0.22	0.22	0.22
			Middle	0.76	0.74	0.69	0.60	0.57	0.53	0.43	0.41	0.37
			Long	1.49	1.11	0.86	1.19	0.86	0.64	0.88	0.59	0.40
	Realistic Progress	Target year	Short	0.33	0.33	0.33	0.29	0.29	0.29	0.26	0.26	0.26
			Middle	0.96	0.93	0.86	0.73	0.70	0.65	0.52	0.50	0.45
			Long	1.92	1.43	1.11	1.49	1.06	0.79	1.06	0.71	0.48
	Higher progress	Target year	Short	0.41	0.41	0.41	0.36	0.36	0.36	0.32	0.32	0.32
			Middle	1.32	1.28	1.19	0.97	0.93	0.86	0.66	0.63	0.57
			Long	2.78	2.06	1.60	2.01	1.44	1.07	1.35	0.91	0.62

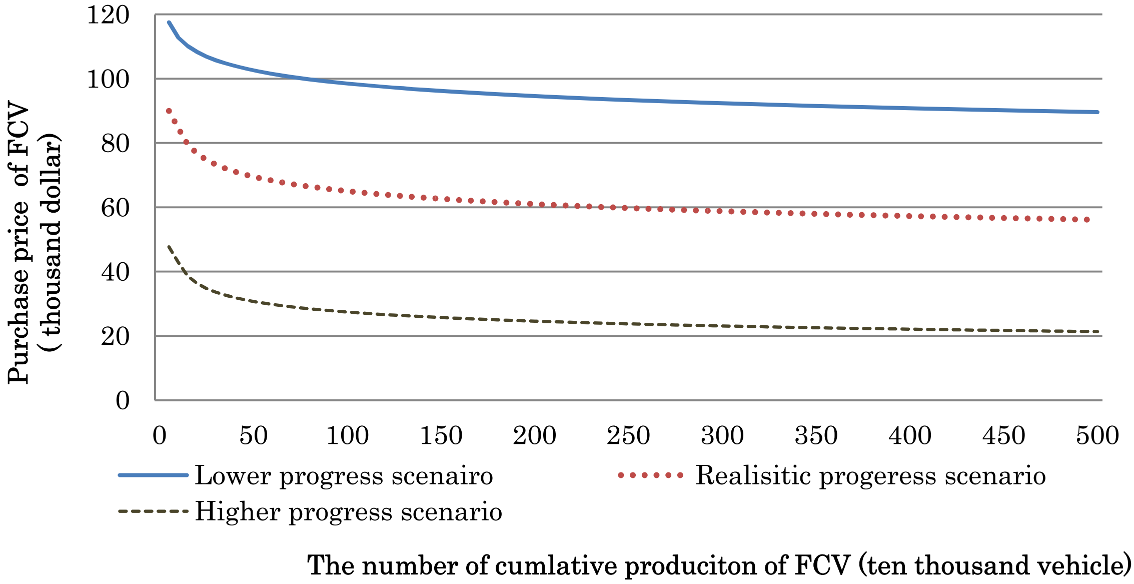

Fig.1 Purchase price of FCVs considering progress ratio

The progress ratio of Lower, *Realistic*, and Higer progress scenario is each 0.96, 0.94 and 0.90, respectively. This means that in the case of lower progress scenario, the purchase price of FCVs decrease 4% when the number of produciton is doubled.

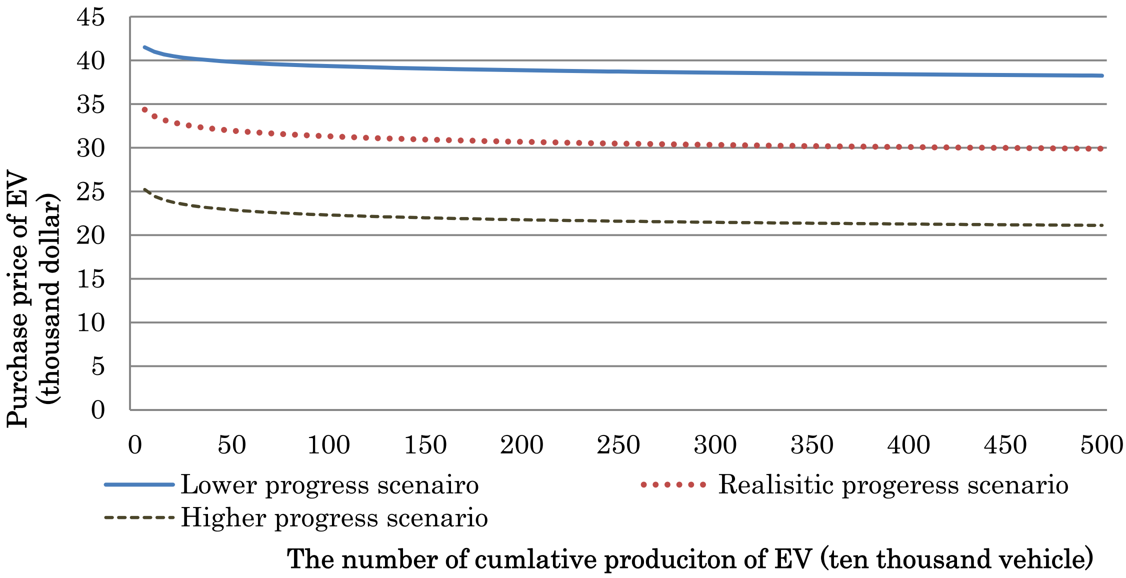

Fig.2 Purchase price of EV considering progress ratio

The number of lower, middle, and higer progress ratio is each 0.98, 0.96 and 0.92, respectively.

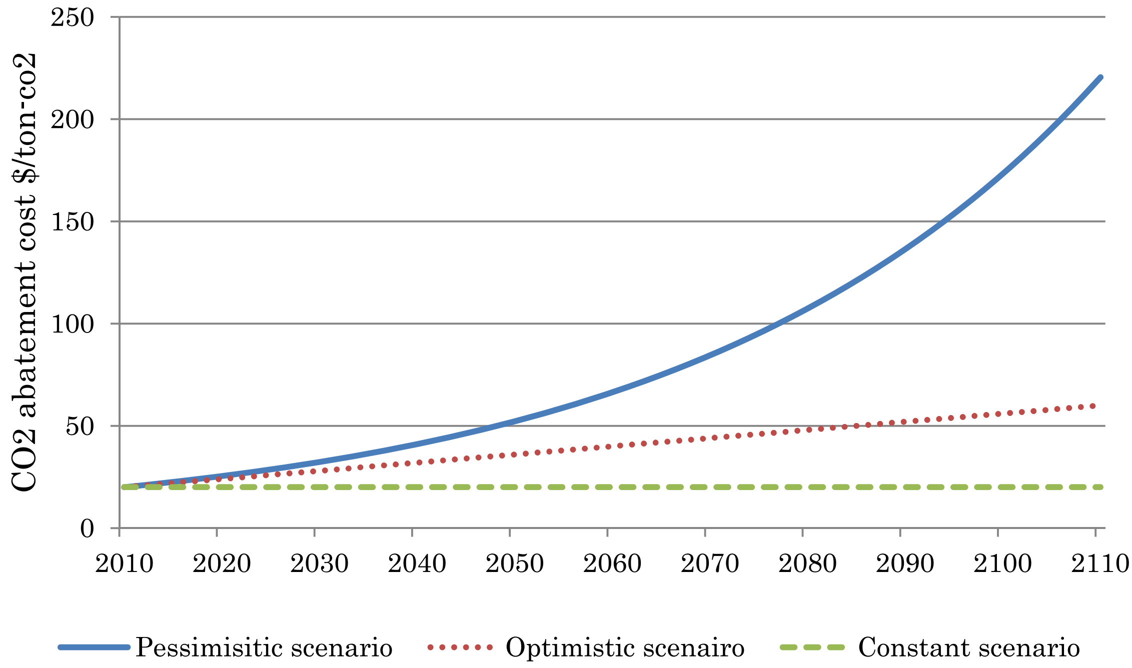

Fig.3 CO2 abatement cost of each scenario

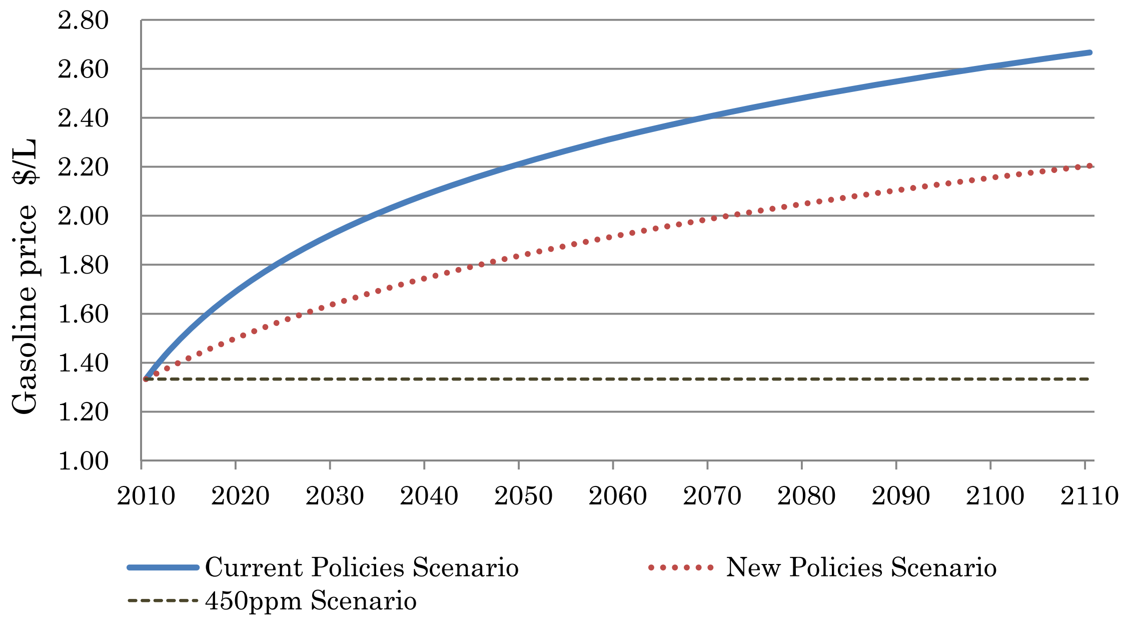

Fig.4 Oil price of each scenario

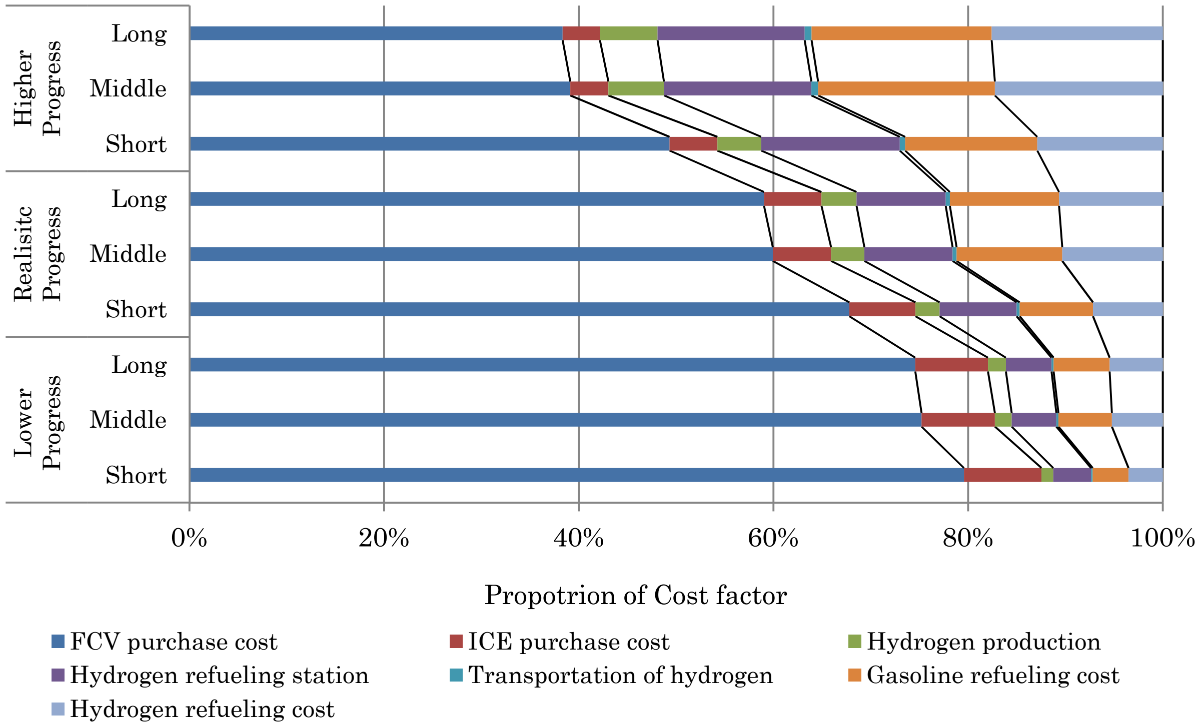

Fig.5 The proportion of Cost factors for FCV diffusion scenarios.

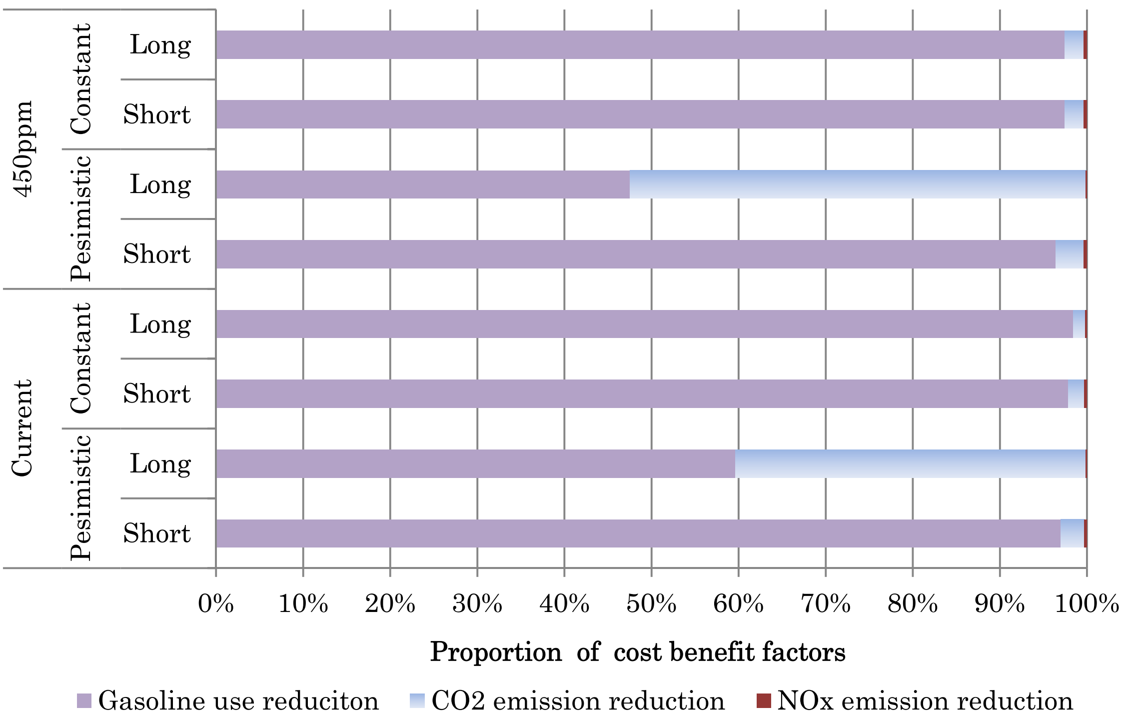

Fig.6 The proportion of Benefit factors for FCV diffusion scenarios.

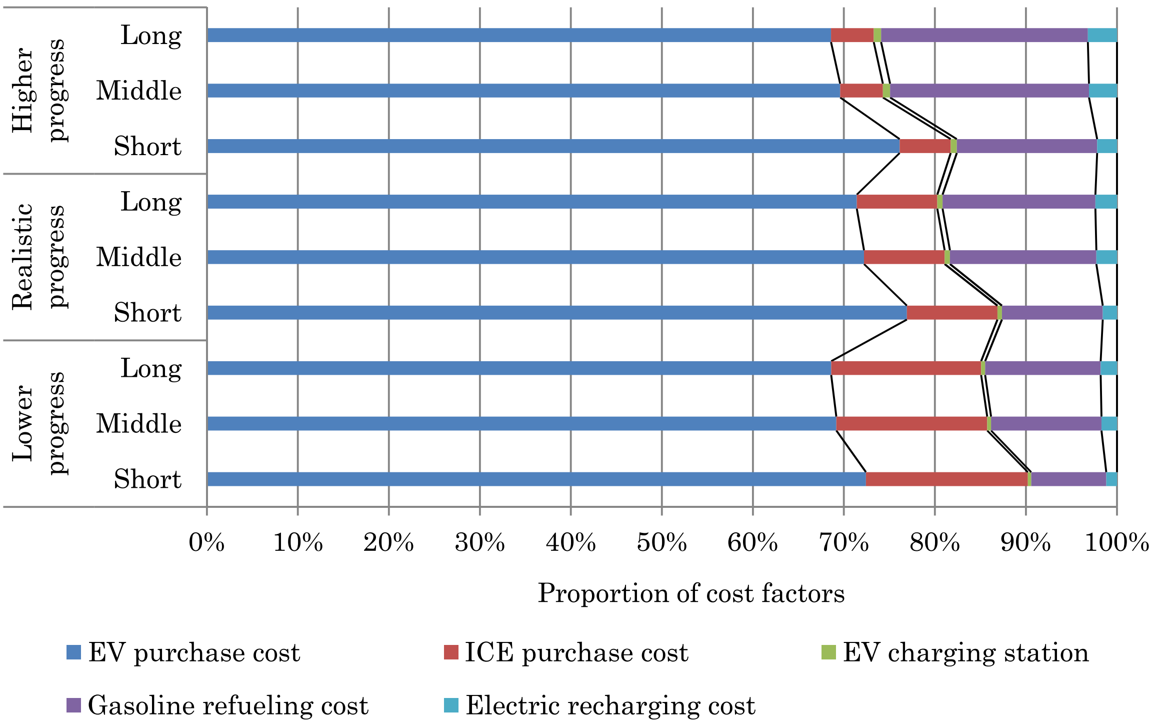

Fig.7 The proportion of cost factors for EV diffusion scenarios

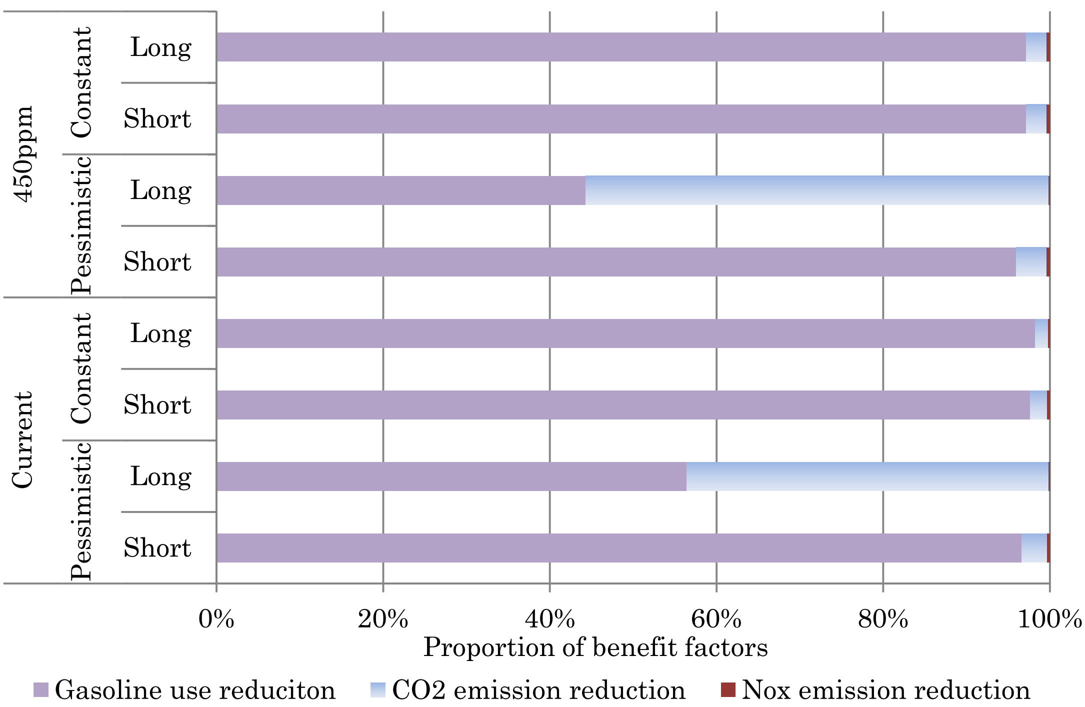

Fig.8 The proportion of benefit factors for EV diffusion scenarios

Appendix

The number of hydrogen supply station (HST) is defined as follows.

$$HST_t = H_{t,production} / CHST \qquad (A-1)$$

where $H_{t,production}$ indicates the amount of hydrogen production for refueling FCVs in year *t* and $CHST$ means the annual supply capacity of one HST. $H_{t,production}$ is estimated as follows.

$$H_{t,production} = NAV_{t,FCV} \times TD / FC_{FCV} \qquad (A-2)$$

As we mentioned in Section.2, $NAV_{t,FCV}$ means the net number of alternative vehicles, (number of FCVs), in year *t* and TD indicate the travel distance of vehicle. FC_{FCV} represents the fuel consumption of FCVs.

As in HST, the number of recharging station (RST) is defined as follows.

$$RST_t = E_{t,production} / CRST \qquad (A-3)$$

$E_{t,production}$ indicates the amount of electricity production for recharging EVs in year *t* and $CRST$ is the annual charging capacity of one RST. $E_{t,production}$ is estimated as follows.

$$E_{t,production} = NAV_{t,EV} \times TD / EM_{EV} \qquad (A-4)$$

where $NAV_{t,EV}$ is the net number of EVs in year t. EM_{EV} means the electric mileage of EV. Initial cost and maintenance cost of HST and RST are represented as each Table A-1 and A-2

Initial cost and maintenance cost of HPP in year t is estimated by Engineering model in Eqs.(A-5) and (A-6).

$$HPP_{t,initial\cos t}\left[dollar\right]=4.3\times\left(\frac{CHPP_t\left[Nm^3/h\right]}{0.9}\right)^{0.68} \qquad (A-5)$$

CHPP means that the capacity of hydrogen purification plant in each prefecture where nuclear plant is located.

$$\begin{aligned} HPP_{t,maintenance}\left[dollar\right]=HPP_{t,initial}\left[dollar\right]\times(0.075+0.075\times Unit\, capacity\;\; factor\left[\%\right]) \\ +CHPP_t\left[Nm^3/h\right]\times 3.54/0.826\times 365\left[day/year\right] \\ \times 24\left[hour/day\right]\times \text{Electric power consumption }\left[\text{dollar/kwh}\right] \qquad (A-6) \end{aligned}$$

Eqs.A-5 to A-6 are obtained from the industry survey to automobile manufacturing company in Japan.

The hydrogen transportation cost (HTC) of track is defined as follows.

$$HTC_t = H_{t,transport} + TR_t \qquad (A-7)$$

$H_{t,transport}$ means the transportation cost of hydrogen by track and it is estimated below.

$$H_{t,transport} = CT\times 2D\times NT_t \qquad (A-8)$$

where *CT* indicates the transportation cost of track per kilometer and *D* shows the distance from HPP to HST. We assume that, in case of prefecture in which nuclear plant is located, the D is half square root of its area. While, in case of prefecture where there is no nuclear plant, the D is distance from prefecture where nuclear plant exist to prefecture where nuclear plant does not exist. These data are obtained from Load solution net (1990). NT_t shows the number of hydrogen supply in year t from HPP to HST and it is estimated as bellow.

$$NT_t = H_{t,production} / CTR \qquad (A-9)$$

The meaning of *CTR* is the capacity of hydrogen transportation of track. $H_{t,trailer}$ is the track production cost and maintenance cost in year *t* and it is required as follows.

$$TR_t = TR_{t,production} + TR_{t,mentenanec} \qquad (A-10)$$

where $TR_{t,production}$ is the production cost of track and $TR_{t,mentenanec}$ is the maintenance cost of track. $TR_{t,production}$ is estimated by multiple the number of track production NTR in year *t* and the production cost of track. NTR_t is indicated in follow Eqs.

$$NTR_t = NT_t / NRT_t \qquad (A-11)$$

where NRT_t means the number of round transportation from HPP to HTS of track in year *t*and it is required as Eqs.

$$NRT = OT / RT \qquad (A-12)$$

where OT is the operation time of track and RT is the time of round transportation of track from HPP to HST. RT is sum of transportation time (TT) and hydrogen supply time (ST) and TT is also estimated as follow.

$$TT = 2D / TS \qquad (A-13)$$

where TS means the speed per kilometer of track. We represent the specification of track in Table.A-3.

Gasoline price is estimated as follows.

$$Gas_t = \alpha + \beta_{oil} Oil_t + \varepsilon_t \qquad (A-14)$$

where the variables are defined as follows:

Gas_t: gasoline price in year *t*.

Oil_t: oil price in year *t*.

ε_t: error term

Table A-1.The construction and operating expenses of hydrogen supply station (100m^3/h).

Specification	Parts	Price of each parts (Thousand dollar)
Hydrogen station specific equipment expected to reduce cost by following diffusion.	Dispenser unit	133
	Pressure accumulator	50
	Boosting transformer	211
	Progress ratio	11
The equipment cost expected to reduce by mass production.	Valve	11
	Electrical instrumentation	69
	Progress ratio	11
The equipment cost expected to reduce by improving learning level and rationalization	Instrumentation and electrical construction	33
	Installation	127
	Design and application cost	62
	Progress ratio	11
The equipment cost are constant despite with or without diffusion	Foundation cost	373
	Utility system	29
	Other equipment	106
	Progress ratio	11
Annual management expenses	Land cost	39
	Employment cost	89
	Electricity expense	11
	Industrial water	1
Expense of refueling hydrogen		1.1 $/kWh

Those data are obtained from NEDO (2007). NEDO (2007) describe the three type of HST. That is 100m^3/h, 300m^3/h, and 500m^3/h. In this study, we consider the comprehensive diffusion of FCVs in Japan. Therefore, it is better to locate HST in many areas that why we choose the 100m^3/h type of HST.

Table A-2.The construction and operating expenses of recharging station.

Factor	Specification
Initial cost of RST	11.1 (1000 $)
Annual maintenance cost of RST	1.1 (1000 $)
Initial cost of fast charger	4.4 (1000 $)
Annual maintenance cost of fast charger	4.4 (1000 $)
Expense of recharge	0.12 $/kWh

Those data are obtained from interview survey to one of the largest automobile manufacturing company in Japan.

Table A-3. The specification of track.

Factor	Specification
Production cost	122 (1000$)
The hydrogen capacity of track	2740 Nm3
Pressure	20 Mpa
Annual maintenance cost	12.4 (1000$)
Speed per kilometer	20 km/hr/ 60 km/ hr
Hydrogen supply time	1 hr

As in Table A-1, these data are obtained from NEDO (2007). The speed per kilometer is 20 km/hr in case of hydrogen transported to the area where nuclear plant is located, i.e., the HPP is founded, while, it is 60 km/hr incase that hydrogen is transported to the area where there is no nuclear plant.

Table A-4. Total cost of FCV diffusion scenario. (Billion dollar)

Progress ratio	Target year	Current policy scenario	New policy scenario	450 ppm oil scenario
Lower progress	Short	384	386	388
	Middle	434	441	451
	Long	310	317	326
Realistic	Short	173	175	177
	Middle	187	195	205
	Long	133	140	149
Higher progress	Short	83	85	87
	Middle	86	94	103
	Long	60	67	76

Table A-5. Total benefit of FCV diffusion scenario. (Billion dollar)

Target year	Current policy scenario			New policy scenario			450ppm oil scenario		
	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant
Short	23	23	23	21	21	21	19	19	19
Middle	57	55	52	49	47	44	39	38	34
Long	70	53	42	63	46	35	54	37	26

Table A-6. Total cost of EV diffusion scenario. (Billion dollar)

Progress ratio	Target year	Current policy scenario	New policy scenario	450 ppm oil scenario
Lower progress	Short	83	85	87
	Middle	75	83	92
	Long	49	56	65
Realistic	Short	71	73	74
	Middle	60	68	77
	Long	38	45	54
Higher progress	Short	56	59	60
	Middle	44	51	61
	Long	26	33	43

Table A-7. Total benefit of EV diffusion scenario. (Billion dollar)

Target year	Current policy scenario			New policy scenario			450ppm oil scenario		
	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant	Pessimistic	Optimistic	Constant
Short	23	23	23	21	21	21	19	19	19
Middle	57	56	52	50	48	44	40	38	35
Long	74	55	42	67	48	36	57	39	26