Analysis of the impact of fuel cell vehicles on energy systems in the transportation sector in Japan

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Abstract

This research examines the changes of energy systems in the transportation sector having fuel cell vehicles (FCVs) in Japan. The concern with FCVs as an advanced transportation technology has been growing in mosts part of developed countries. FCVs are planed to be introduced in the transportation market in 2003 by the year around through automobile manufactures in Japan. The advantage of having FCVs could be summarized as follows; (1) reduction of energy consumption with the high efficiency of fuel cells, (2) followed by the reduction of carbon dioxide emissions in the transportation sector, (3) possibility of energy shift from petroleum to the other fuel resources, such as natural gas and renewables. FCVs has strong possibility to solve the environmental issues such as fossil fuels combustion and the mitigation of carbon dioxide emissions, however, the cost such as passenger transportation cost and capital cost of FCVs is higher than that of conventional vehicles. Therefore, in this study, we assume that the tax revenue which is gained by carbon tax is returned to the costs of FCVs as subsidies. From the result of our study, it is revealed that the subsidy for FCVs has an effect to accelerate the introduction of FCVs. In particular, the subsidy for the cost of passenger transportation of FCVs has an impact on the passenger transportation market.

1. Introduction

In the latter of the 1990s, the concern with the introduction of fuel cell vehicles (FCVs) as a new technology solving the environmental and energy issues in the transportation sector has been growing. Recently, rapid advances in fuel cell performance is achieved by private industries such as Ballard Power Systems (Weiner, 1998). Then it has stimulated increased interest of the research and development of FCVs in the U. S. A., Europe and Japan (Chalk, 1998).

In Japan, the transportation sector accounted for 22% of total carbon dioxide emissions, and carbon dioxide emissions from the transportation sector is still growing in spite of current recession in economy. In Japan's transportation sector, as the carbon dioxide emissions from automobiles accounted for 88% of total emissions, it is important to develop advanced transportation technologies as well as improving conventional fuel engines.

Although the introduction of FCVs have many advantages such as the reduction of both energy consumption with the high efficiency of fuel cell and carbon dioxide emission, there is some questions; the cost of FCVs is expensive and the infrastructure of fuel supplies must be improved.

The FCVs have several types of vehicles based on fuel resources (e.g. petroleum, natural gas, biomass etc.) and the way of fuel supplies (onsite hydrogen station, onboard steam reforming). It is expected that FCVs' costs and energy consumption, and the impact of FCVs on carbon emissions in the transportation sector differ with the types of FCVs. Thus, it is necessary to examine which types of FCV is appropriate from the long-term view of technical specifications and its economic aspects.

Several studies have been conducted on the possible introduction of FCVs by many researchers. Hart studied the introduction of FCVs using methanol as liquid fuel in Europe, North America and Japan (Hart, 2000). In this study, the model which has different set of regional parameters was used to examine the possibility of FCVs to archive market

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penetration in the passenger transportation sector. The economic aspects of FCVs using hydrogen and methanol as fuel resources were analyzed by using Fuzzy Set-Based Framework (Lipman, 1998). Moreover, introduction of carbon tax on energy systems were examined by many researchers. Williams analyzed optimal policy such as carbon taxation by using global warming model (Williams, 1995).

However, very few attempts have been made on the research which consider both energy conversion efficiencies and economic aspects such as capital cost and competitive power in the FCVs market from the long-term view. And there has been no study that analyzed the return of tax revenue from carbon taxation as the subsidy for FCVs. In this paper, we develop an energy-economic model to consider both economic aspects and energy conversion efficiencies differed with fuel resources and the way of fuel supplies. By analyzing this model, we examine the introduction of FCVs which have several types of fuel resources and the way of fuel supplies. And then, we analyze the impact of carbon tax on the introduction of FCVs and explore effective option to accelerate the introduction of FCVs.

2. An energy-economic model

2.1. Japan model

We have developed detailed model in the passenger transportation sector based on the Japan model which have been designed by Nakata et al. (Nakata, 2000; 2001). The Japan model is shown in Figure 1. It has 69 processes; includes eight demand nodes in the industrial, commercial, residential and transportation sectors; and contains ten resource nodes modeling purchases of coal, natural gas, petroleum and nuclear fuel on the world markets. Additional processes model electricity sector, transportation services, and the conversion of fuel to heat. Nakata et al. analyzed the impact of the carbon taxes on energy systems in Japan using this model. In this study, we focus on the passenger transportation sector. The Japan model runs from the year 1999 to 2044 under the time step of 5 years period.

2.2. Passenger transportation model

Eight types of transportation sector model is shown in Figure 2. We have defined the following FCVs models from FCV-0 to FCV-7 in the passenger transportation sector in which fuel resources and the way of fuel supplies are different. Table 1 summarizes the fuel resources and the fuel supply systems. The specific characteristics of each model are given below in detail.

a) FCV-0

There is no FCVs in the passenger transportation market. Both conventional gasoline vehicles and hybrid vehicles exist in the market. This model presents the business as usual case.

b) FCV-1

The FCVs which use petroleum as a fuel resource is introduced in the transportation market. Petroleum is refined from crude oil, and then supplied to FCVs at the gas station. Hydrogen is reformed from petroleum in a compact reformer on the vehicle, and supplied to the fuel cell.

c) FCV-2

The FCVs use petroleum as a fuel resource as seen in FCV-1. In this model, hydrogen is reformed from petroleum at the onsite hydrogen station in advance, and directly supplied to FCVs.

d) FCV-3

The FCVs use natural gas as a fuel resource. Methanol is produced from natural gas, and then supplied to FCVs at the conventional gas station. Hydrogen is reformed from methanol in a compact reformer on the vehicle.

e) FCV-4

The FCVs use natural gas as a fuel resource as seen in FCV-3. Hydrogen is reformed from natural gas at the onsite hydrogen station, and then directly supplied to FCVs.

f) FCV-5

The FCVs use biomass as a fuel resource. Methanol is produced from biomass, and then supplied to FCVs at the conventional gas station (Bull, 1996). Hydrogen is reformed form methanol in a compact reformer on the vehicle.

g) FCV-6

The FCVs use biomass as a fuel resource as seen FCV-5. Methanol is produced from biomass. Hydrogen is reformed from methanol at the onsite hydrogen station, and then directly supplied to FCVs.

h) FCV-7

The FCVs use water and electricity as a fuel resource. Hydrogen can be produced from electricity via electrolysis at the onsite hydrogen station, and then directly supplied to FCVs (Berry, 2001).

The energy flow from fuel resources to the output of automobiles in each models is illustrated in Figure 3, showing energy conversion efficiencies and well to wheel efficiencies which are obtained by multiplying energy conversion efficiencies of each processes. The SCC (Specific Capital Cost) means the capital cost of onsite hydrogen station and FCVs etc., and the AOC (Ancillary Operating Cost) means its operating cost. These parameters are carefully examined from the current references (Thomas, 1998; World Energy Council, 1998; Matsuoka, 2000; Energy Data and Modeling Center, 1999).

2.3. Carbon tax

The cost of passenger transportation and the cost of vehicles of FCVs are higher than that of conventional gasoline vehicle and hybrid vehicle. Since these price differences obstruct the introduction of FCVs, it is important for the introduction of FCVs to reduce the cost of passenger transportation such as capital cost and operating cost.

A carbon tax is expected to be an efficient approach to reduce carbon dioxide emissions. It has been already implemented in Sweden and Denmark in 1990s. A carbon tax will raise the price of high-carbon fuels such as coal and petroleum, and promote the energy shift from high-carbon fuels to low-carbon fuels such as natural gas.

In this study, it is assumed that a carbon tax is imposed for the way of reducing the price difference between FCVs and conventional vehicles. To mitigate the impact of carbon taxation on energy systems, the taxes were introduced gradually over time, increasing the tax rate in uniform steps each period until the maximum rate in 2044 was reached.

Large amount of tax revenue is gained by the imposition of carbon tax. In Northern European countries, tax revenue are used as general finances. In this study, it is assumed that tax revenue is used as the subsidy for the introduction of FCVs. The return scenarios of tax revenue are given below.

a) No return

There is no subsidy for the cost of FCVs.

b) Return to the capital cost (Return-C)

It is assumed that tax revenue is used as the subsidy for the specific capital cost of FCVs.

c) Return to the passenger transportation cost (Return-P)

It is assumed that tax revenue is used as the subsidy for the passenger transportation cost of FCVs.

Since the transportation sector accounted for 22% of total carbon dioxide emissions, the total amount of subsidy took 22% of the amount of carbon tax revenue.

2.4. Tools for the analysis

In this study, we have used the META•Net economic modeling system which was developed at the Lawrence Livermore National Laboratory. The META•Net is a partial equilibrium modeling system that allows for explicit price competition between technologies, and can constrain or tax emissions. It allows a user to built and solve complex economic models. Although the changes in the economy are largely driven by consumers' behavior and the costs of technologies and resources, they are also affected by various government policies. These can include constraints on prices and quantities, and various taxes and constraints on environmental emissions. The META•Net can incorporate many of these mechanisms and evaluate their potential impact on the development of the economic system (Lamont, 1994).

2.5. Initial conditions for the analysis

Several key assumptions are required to drive any analysis of this type. These include growth rates and demand response to changes in price. In this study, we assumed a moderate rate of growth over the time horizon. Table 2 shows the assumptions for the growth and demand elasticities in each sectors. Aviation transportation demand is not included in the transportation sector because the energy share of aviation is less than 5%. Hybrid vehicles were introduced to the market in the end of 1997 and became popular in 1999 in Japan. Therefore, hybrid vehicles are assumed to be available in the transportation market in the year 1999. As for the introduction of FCVs, major automobile manufactures in Japan plan to introduce FCVs into the market in 2003 by the year around. Thus, FCVs are assumed to be available in the year 2004 in this model.

3. Results of the analysis

3.1. The transportation cost and passenger transportation of FCVs

The discussion in this section highlights the analytical results of the cost of passenger transportation and the passenger transportation of FCVs.

First, the cost of passenger transportation are shown in Figure 4. Under the condition that the vehicles use same fuel resources, the cost of passenger transportation fueled by onsite hydrogen (FCV-2, FCV-4) becomes lower than the cost fueled by onboard steam reforming. Then, Under the condition that FCVs use the same fuel supplies, natural gas (FCV-3, FCV-4) has priority in the cost of passenger transportation.

Second, the growth of passenger transportation of FCVs are shown in Figure 5. The growth rate of passenger transportation depends on the cost of passenger transportation. Between FCV-4 and FCV-7, which have largest difference in the cost of passenger transportation, the passenger transportation of FCV-4 is 11 times larger than that of FCV-7.

3.2. The passenger transportation of FCVs when carbon tax is imposed

The discussion in this section highlights the analytical results of passenger transportation of FCVs when a carbon tax is imposed.

The passenger transportation of FCVs when the carbon tax is imposed is shown in Figure 6. In the case of carbon taxation, the passenger transportation of FCVs and hybrid vehicles which had high energy conversion efficiency became large. In particular, the increase of FCVs became remarkable. As the tax rate became higher, the passenger transportation of FCVs, which has high energy conversion efficiency and can use low-carbon fuels, became larger. At the tax rate of $80/tonC, the passenger transportation of FCV-2 became 1.20 times larger than that of no taxation case. On the other hand, at the tax rate of $160/tonC, the passenger transportation of FCV-2 became 1.25 times larger than that of no taxation case.

3.3. The passenger transportation of FCVs when tax revenue is returned

The discussion in this section highlights the analytical results of passenger transportation of FCVs when the tax revenue is returned to costs of FCVs.

First, the specific capital costs of FCVs with or without tax return in the year 2044 are shown in Table 3. And then, the passenger transportation costs of FCVs with or without tax return in the year 2044 are shown in Table 4. By using the tax revenue as the subsidy, the specific capital cost and the cost of passenger transportation became lower than that of no subsidy case. In particular, under the condition that the cost of passenger transportation was subsidized, the cost difference between FCVs and conventional vehicles became small.

Second, the passenger transportation of FCVs is shown in Figure 7 with the tax rate of \$80/tonC and in Figure 8 with the tax rate of \$160/tonC. By subsidizing the costs of FCVs, the introduction of FCVs is greatly accelerated. Under the condition that the specific capital cost was subsidized, the passenger transportation of FCVs became 1.07-6.83 times as large as that of no subsidy case. Under the condition that the passenger transportation cost is subsidized, the passenger transportation of FCVs became 2.05-19.5 times as large as that of no subsidy case.

4. Conclusion

In this study, we have developed an energy-economic model which we can take both energy conversion efficiencies and the economic aspects into consideration. Then we have evaluated the impact of FCVs on energy systems in the transportation sector in Japan. The result of our analysis shows that FCVs, in which the fuel is supplied at onsite hydrogen station and fuel resources is natural gas, shows optimal system.

Then, we have analyzed the effect of carbon tax on the cost difference among FCVs, conventional gasoline vehicles and hybrid vehicles. Carbon tax can mitigate the cost difference, and promote the introduction of FCVs. Moreover, the result of our analysis shows that the tax return to the costs of FCVs has the strong effect on the introduction of FCVs. In particular, the subsidy for the passenger transportation show larger effect than that for the specific capital cost.

References

Berry, G., Lamont, A. and Watz, Jill. (2001) Synergies in Renewable Energy Systems. UCRL-JC-141615. Lawrence Livermore National Laboratory, Livermore, California.

Energy Data and Modeling Center. (1998) *EDMC Handbook of Energy & Economic Statistic in Japan*, Tokyo.

Hart, D., Leach, M.A., Fouquet, R., Pearson, P.J. and Bauen. A. (2000) Methanol infrastructure – will it affect the introduction of SPEC vehicles? *Journal of Power Sources* **86**, 542-547.

Lamont, A. (1994) User's Guide to the META•Net Economic Modeling System Version 1.2. UCRL-ID-122511. Lawrence Livermore National Laboratory, Livermore, California.

Lipman, T.E. (1998) Zero-emission vehicle scenario cost analysis using a fuzzy set-based framework. Ph.D. dissertation, UCD-ITS-RR-99-18. University of California, Davis, California.

Matsuoka, Y. (2000) Study on hydrogen refueling station and its R&D subjects. *Energy and Resources* **21** (1), 56-61.

Nagata, Y. (2000) Personal communication. June 21, 2000.

Nakata, T. (2000) Analysis of the impact of hybrid vehicles on energy systems in Japan. *Transportation Research Part D* **5**, 373-383.

Nakata, T. and Lamont, A. (2001) Analysis of the impacts of carbon taxes on energy systems in Japan. *Energy Policy* **29**, 159-166.

Ogden, J.M., Steinbugler, M.M. and Kreutz, T.G. (1999) A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicles design and infrastructure development. *Journal of Power Sources* **79**, 143-168.

Thomas, C.E., James, B.D. and Lomax Jr., F.D. (1998) Market penetration scenarios for fuel cell vehicles. *Hydrogen Energy* **23** (10), 949-966.

Weiner, S.A. (1998) Fuel cell stationary power business development. *Journal of Power Sources* **71**, 61-64.

Williams, M. (1995) Global warming and carbon taxation *Energy Economics* **17** (4), 319-327.

World Energy Council. (1998) *Survey of energy resources 1998*, London.

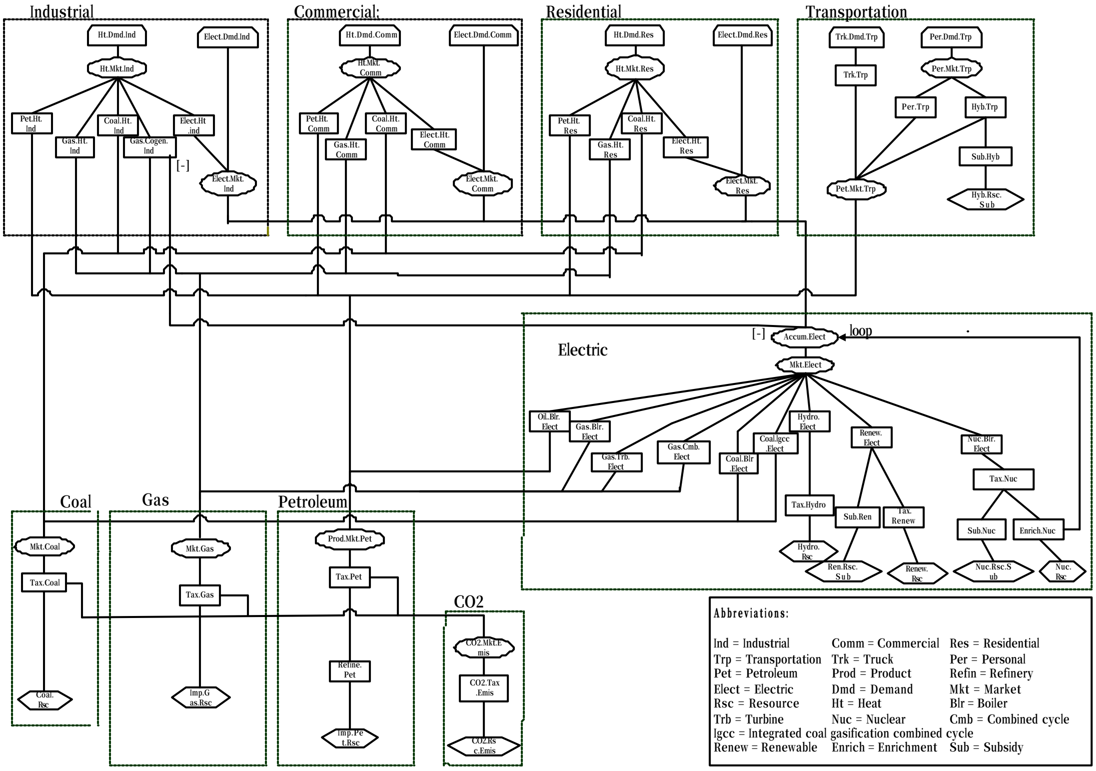

Fig. 1. Japan model

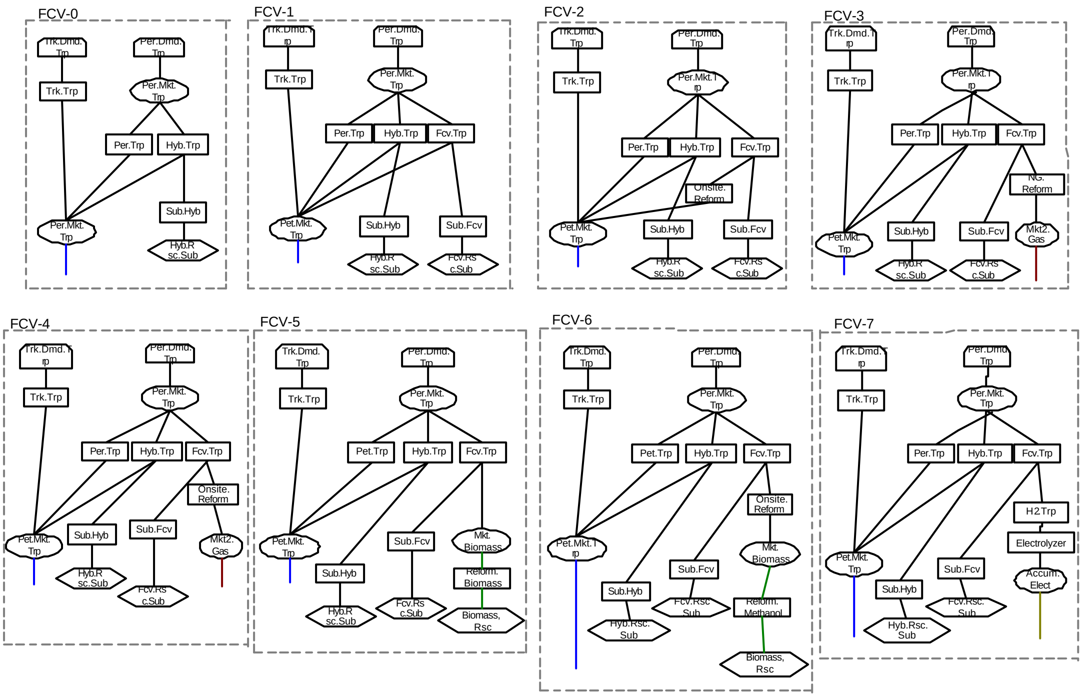

Fig. 2. Models of the transportation sector for each FCVs

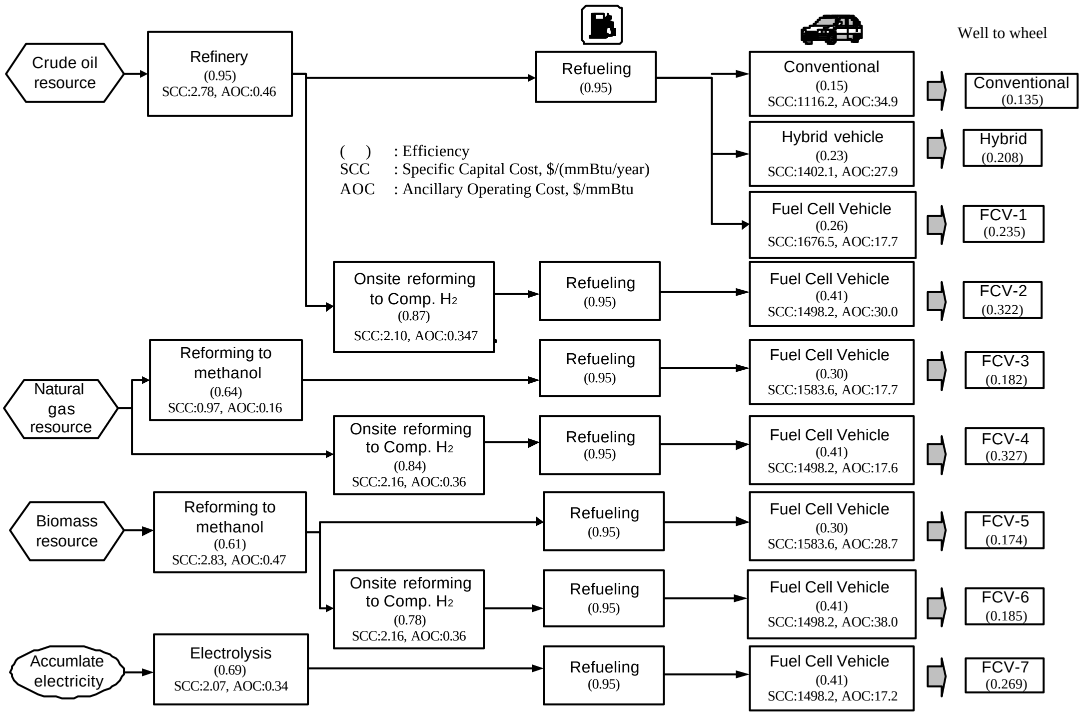

Fig. 3. Energy flow from well to wheel for each models

Table 1 The way of fuel supply of each FCVs

Type	Fuel resource	Onsite reformer	Charged fuel to the vehicle	Onboard reformer
FCV-0	Petroleum	None	Gasoline	None
FCV-1	Petroleum	None	Gasoline	○
FCV-2	Petroleum	○	H_2	None
FCV-3	Gas	○	Methanol	○
FCV-4	Gas	○	H_2	None
FCV-5	Biomass	○	Methanol	○
FCV-6	Biomass	○(Methanol→H_2)	H_2	None
FCV-7	*1	○	H_2	None

*1 H_2 is derived from H_2O by electrolysis.

Table 2 Growth rate and elasticity assumptions for end-use sector

Sector	Annual rate of demand growth[a)]	Demand elasticity[b)]
Industrial heat demand	0.002	-0.340
Industrial electricity demand	0.007	-0.340
Commercial heat demand	0.012	-0.240
Commercial electricity demand	0.014	-0.240
Residential heat demand	0.006	-0.300
Residential electricity demand	0.017	-0.300
Truck transportation demand	0.003	-0.170
Personal transportation demand	0.010	-0.230

[a)]The Energy Data and Modeling Center (2001).
[b)]Based on the data by Nagata (June 21, 2000, personal communication).

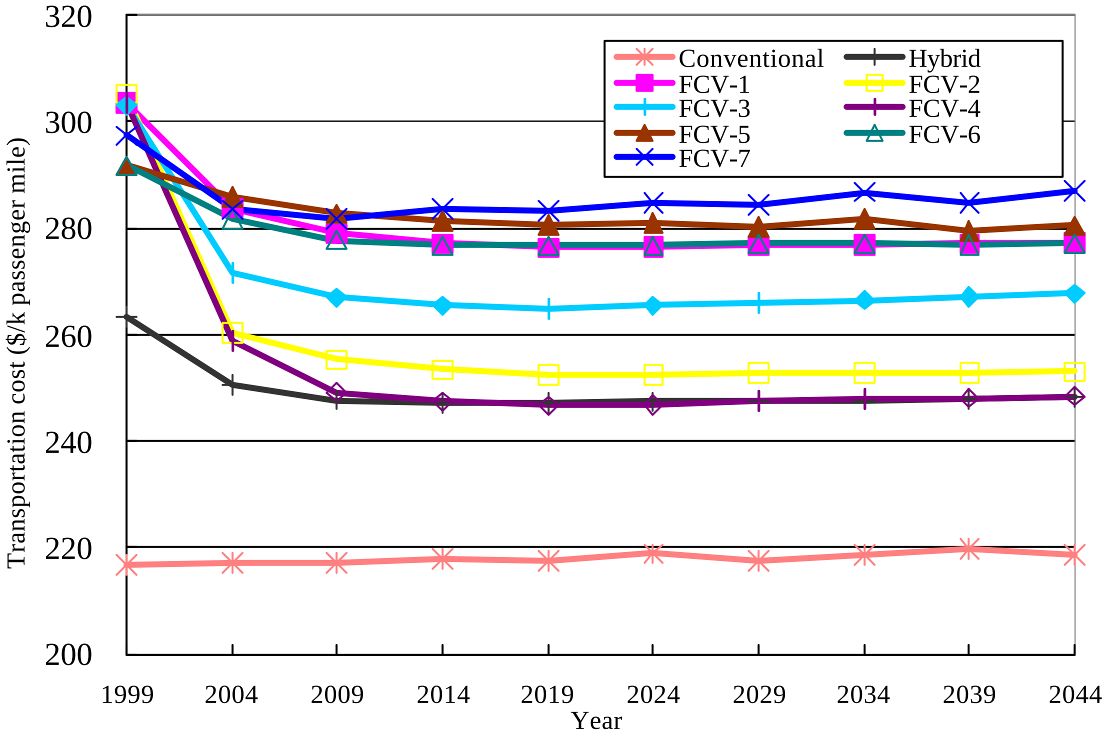

Fig. 4. The passenger transportation cost of FCVs in each models

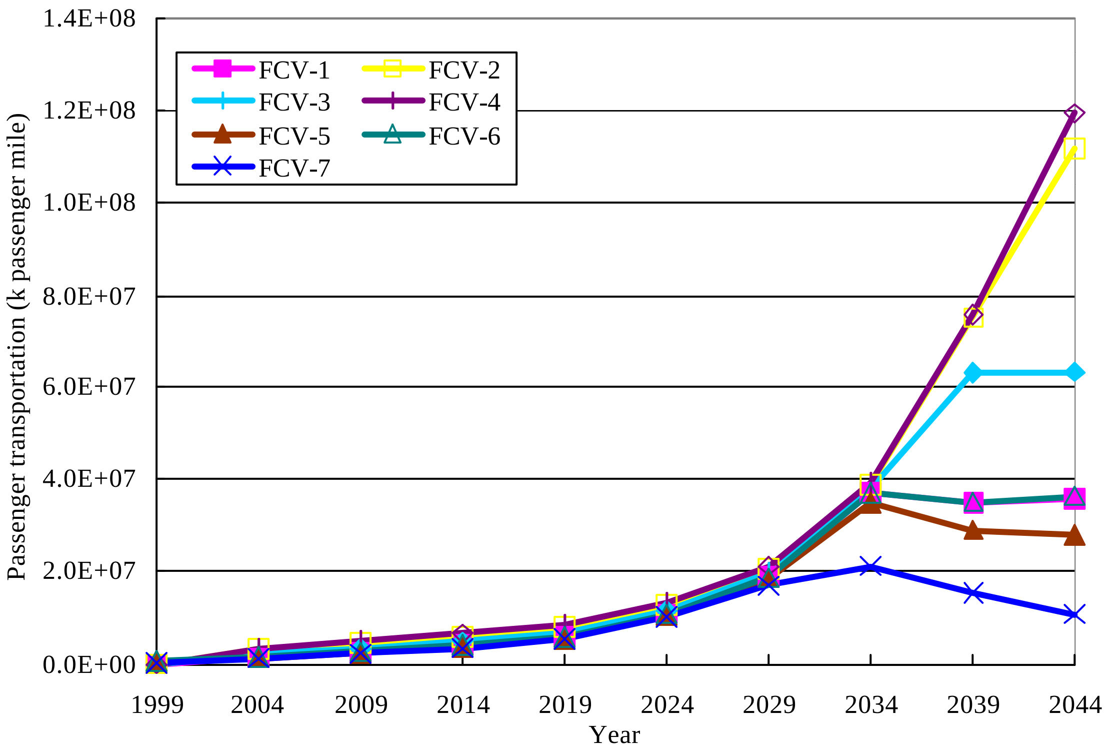

Fig. 5. Passenger transportation of FCVs in each models

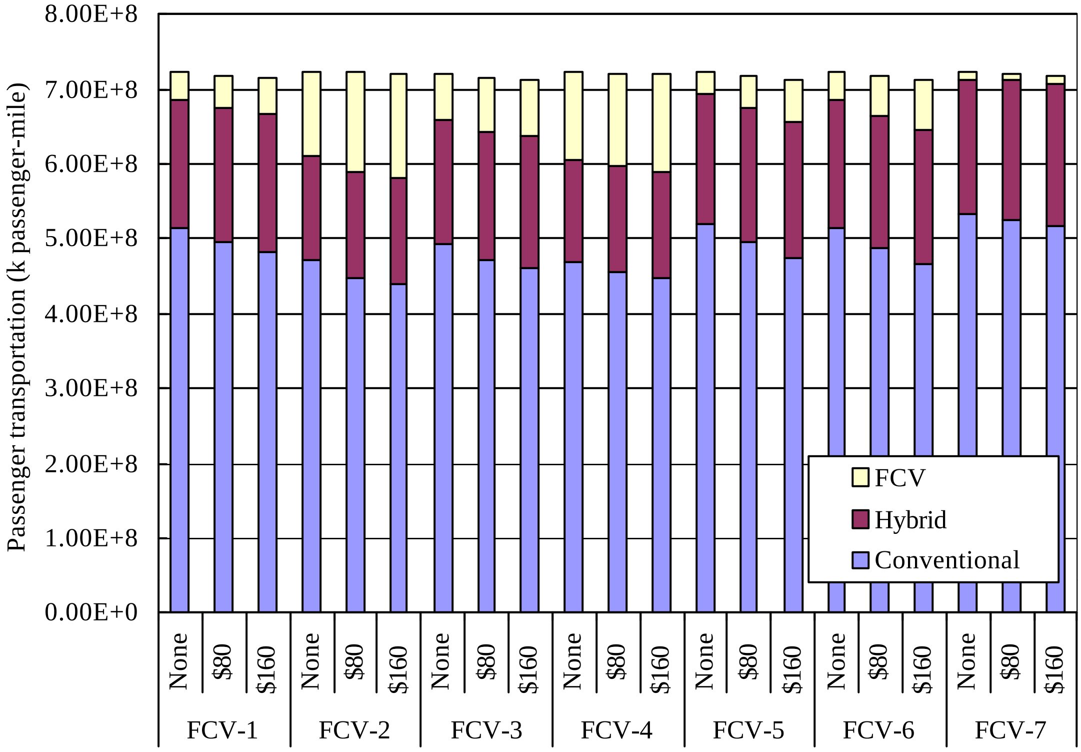

Fig. 6. Passenger transportation when carbon tax is imposed

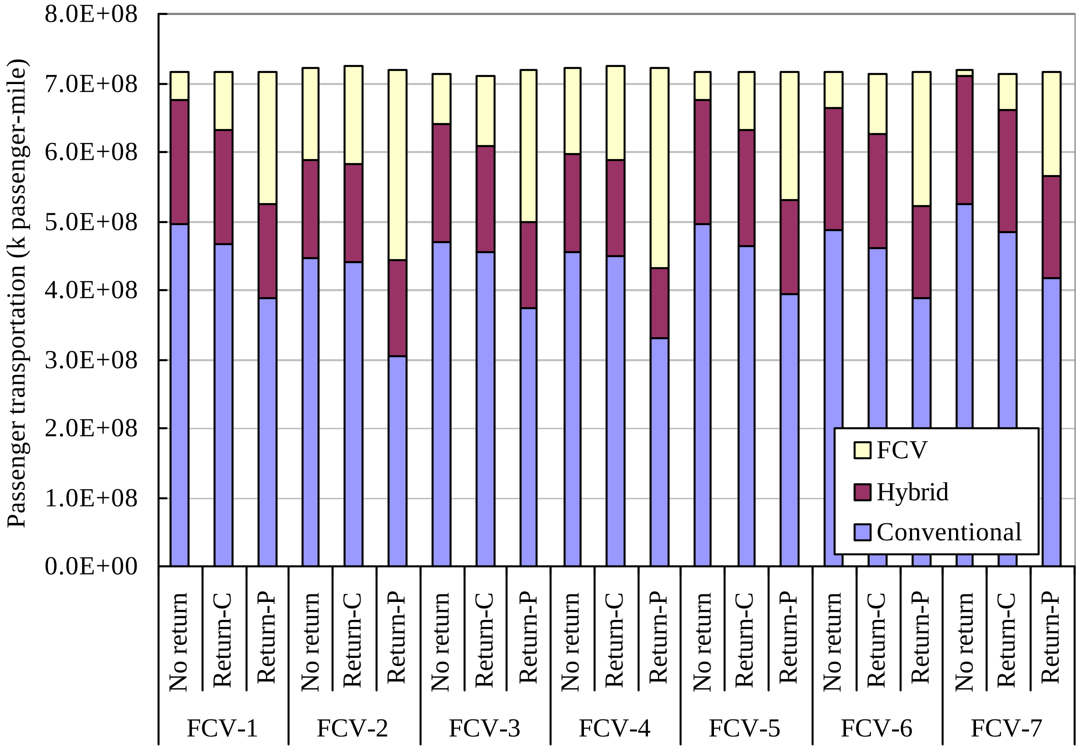

Fig. 7. Passenger transportation with or without tax return under the carbon tax of $80/tonC

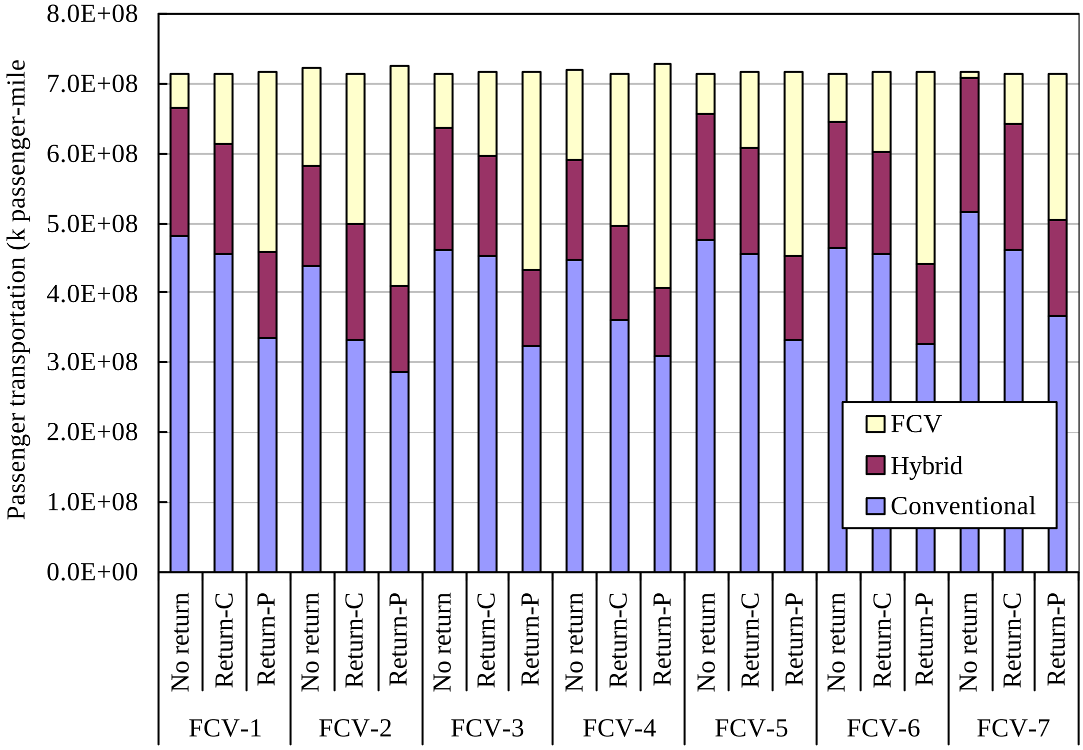

Fig. 8. Passenger transportation with or without tax return under the carbon tax of $160/tonC

Table 3 The specific capital costs of FCVs with or without tax return in the year 2044

($/(k passenger-mile/year))

Tax	Return	FCV-1	FCV-2	FCV-3	FCV-4	FCV-5	FCV-6	FCV-7
No tax	No-Return	1,677	1,498	1,584	1,498	1,584	1,498	1,498
$80/TC	Return-C	1,590	1,450	1,515	1,447	1,497	1,420	1,367
$160/TC	Return-C	1,556	1,443	1,483	1,417	1,471	1,394	1,329

Table 4 The passenger transportation costs of FCVs with or without tax return in the year 2044

($/k passenger-mile)

Tax	Return	FCV-1	FCV-2	FCV-3	FCV-4	FCV-5	FCV-6	FCV-7
No tax	No-Return	277	253	268	248	280	277	287
$80/TC	No-Return	281	254	271	250	281	277	292
	Return-C	244	229	239	227	245	243	248
$80/TC	No-Return	284	255	274	252	281	277	295
	Return-C	238	219	233	216	237	235	241