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A System Dynamics Model of Alternative Fuel Vehicles Market under the Network Effect*

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Abstract

According to the system dynamics model of this study, if there is a significant network effect on vehicle operating costs, it is difficult to achieve the shift to AFV even in the long term without a policy intervention because the car market is locked in to the current structure. Network effect can be caused by an increasing return to scale in fuel supply sector as well as in maintenance service sector. It is also related to the fact that the reliability and awareness of consumers on new products increases with the growth of the market share of the new products. There are several possible policy options to break the 'locked in' structure of car market, such as subsidy on vehicle price (capital cost), subsidy on fuel (operating cost) and niche management policy. Combined policy options would be more effective than relying on a single policy option to increase the market share of AFV.

Keywords: Increasing Returns to Scale, Network Effect, Positive Feedback Effect, Lock in, Alternative Fuel Vehicles, System Dynamics Modelling

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Ⅰ. Introduction

The possibility of substituting Alternative Fuel Vehicles (AFVs) for conventional cars using petrol/diesel has been attracting more and more attention. This is because Alternative Fuel Vehicles (AFVs) such as electricity (hybrid[1]), bio-fuels and fuel cell vehicles have potential to remarkably reduce CO2 emissions, which is the most significant global warming gas, as well as to relieve local air pollution, not to mention the energy security problem of conventional fuels. However, there has been only a marginal development in the AFVs market until now. This study investigates the market barriers in increasing the market share of AFVs and possible policy options to overcome them by using a system dynamics model. In particular, this study focuses on a situation where there are increasing returns to scale for vehicle operating costs. That is, the model assumes that the operating costs of AFVs including fuel supply costs and vehicle maintenance costs have a positive feedback relationship with the scale of overall car stocks sold. System dynamics modelling is a useful approach to model a feedback effect like this situation. System dynamics originated from the work of J. W. Forrester at MIT in the 1950s and has been widely used in various fields, including industrial, urban and environmental systems. In particular, Meadows et al (1972, 1992) provoked huge debates on the issue of sustainable development using such approaches. The system dynamics modelling method can be referred to in Sterman (2000), and Ruth & Hannon (1994, 1997). This study uses the STELLA program (v.9) for the system dynamic modeling.

The key concepts in the following system dynamics model such as 'increasing returns to scale', 'lock in', 'network effect (externality)' are well explained in Arthur (1994) with relevance to the market share behaviour between competitive products. Earlier literature includes Kaldor (1972). The application of these concepts into energy technology can be referred to in Grubler et al. (1999) and Unruh (2000). More specifically, its application to alternative vehicle technology can be referred to Farrel et al. (2003), Kemp et al. (1998) and Winebrake (1997). Also, Sterman (2000, p.391) provides a reference model for system dynamics modelling of increasing returns to scale and path dependence.

Since there is huge uncertainty about future changes in the technology of AFVs, many parameters such as the relative cost of AFVs compared to conventional cars are hypothetically

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1) Hybrid cars use both petrol/diesel engine and electric motors.

given in the model[2]. Thus it should be noted that the purpose of the model building in this paper is not to forecast the change of the market share of AFVs. The primary purpose of the model building in this study is to examine the model behaviour of the future car market share under the specific assumption such as the increasing returns to scale in fuel supply. Also, it would be interesting to learn how the model behaviour changes under different model assumptions.

In the next section, key assumptions of the model are explained. Then in section 3, this study investigates the market barrier that is caused by increasing returns to scales for vehicles operating costs in raising the market share of AFVs. Further to this, section 4 analyses the impact of various policy instruments to overcome the market barrier. Finally, the policy implication of this study is examined in conclusion.

Ⅱ. The Assumptions of the AFVs Market Model

The AFVs market model of this study is based on the following key assumptions. First, it is assumed that the market share between conventional vehicles and AFVs is determined by the total cost of vehicle driving, which is the sum of vehicle price and operating costs (fuel cost and maintenance cost etc.) with twice as much weight to the former[3]. The following logistic function (equation (1)) is suggested for the relationship between the market share of AFVs and the relative cost of AFVs. The logistic function is very widely used to approximate an S-curve growth behaviour such as the diffusion of new products.

$$m(c) = \frac{1}{1+\exp[\alpha + \beta c]} \qquad (1)$$

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2) Some literature such as Ogden et al. (2004) provides estimations of vehicle cost and fuel cost of AFVs including Fuel Cell Vehicles. However, these estimates are based on the assumption of mass production so that the changes in vehicle and fuel supply cost over time, which will be used in the following model of this study can not be drawn from these estimates.

3) This weight is based on a rough estimation that vehicle purchase price is twice vehicle operating cost (fuel cost and mechanical maintenance cost) over 15 years (average life time of vehicles) in terms of present value.

where m is the market share of AFVs, c is the relative total cost of AFVs (the cost of conventional cars =1)[4], and a and b are parameters determining the location and slope of the logistic curve respectively.

Since it is not possible to empirically estimate a and b, the model should be built on hypothetical assumptions on the values of α and β. However, the model needs to assume α =-β to have an equal market share when the relative cost of AFVs is equal to conventional cars[5]. Figure 1 illustrates the changes in the market share of AFVs according to the possible pairs of a and b. The change in market share when the relative cost is below 1 is symmetrical to the change in Figure 1. The model in this study assumes α=-10 and β=10 because it expects a radical change in market share according to the change in the relative cost of car driving. In this case, if the total cost of AFVs is higher than the total cost of conventional cars by 30%, the AFVs have only a 5% market share. When the total cost of AFVs is higher by 20%, its market share increases to about 12% and when it is higher by 10%, it obtains about a 27% market share. The total new car sales volume and the total car fleets have constant values over time in the model.

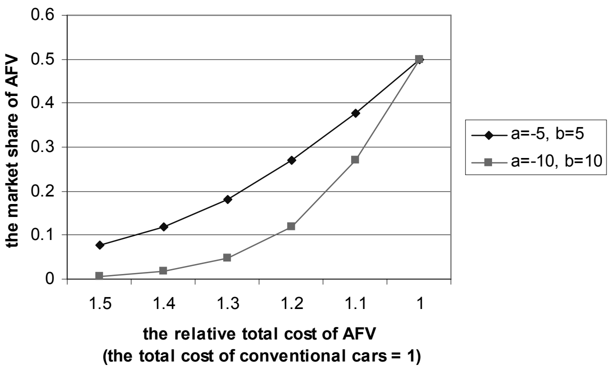

Figure 1 The market share of AFV according to different parameter values of α and β

4) That is, c = the total cost of AFVs / the total cost of conventional cars

5) When m(c) = 0.5 = 1/[1+exp(a + b × 1)] in equation (2.2), as exp(0) = 1, a + b must equal 0 (Cramer, 1991).

Secondly, the relative price of AFVs is assumed to be twice as high as the vehicle price of conventional cars at the initial year (2005) of the simulation period. Then it is assumed that the gap of production cost between the two types of cars declines annually by 10%.

Thirdly, the operating cost of each type of car has positive feedback with the scale of its car stock sold. This assumption is critical for the overall model behaviour as will be illustrated below. The operating cost in this model includes fuel cost as well as vehicle maintenance cost. The cost here should be interpreted as an expected cost of consumers in a broad context, including accessibility to fuel as well as reliability and awareness of car use/maintenance. There are several factors that cause the positive feedback relationship between the operating cost of vehicles and the scale of car stocks. First, it seems that there are increasing returns to scale for the fuel supply sector. It would be more costly per unit to supply fuel to a small number of cars than to a large number of cars. In addition, to provide labour skills and parts necessary for the maintenance of vehicles would also be more costly per unit to cars with a small market share. That is, the unit maintenance costs of vehicles will also decrease as the car stocks sold increase in the market, due to 'learning by doing' in service labour as well as due to increasing returns to scale in parts supply. Finally, the reliability and awareness of vehicle use/maintenance, which will increase with the growth of the market share, will also affect the expected cost of vehicle operation. All these effects are referred to as network effects in this study.

Although vehicle production costs can also be regarded as having a positive feedback relationship with the scale of the sold vehicles in a similar manner to operating cost, this is not considered in this model for the reason that vehicle production cost is likely to be linked to the global scale of the vehicle market rather than the Korea market alone. If the positive feedback relation between vehicle production cost and production scale is taken into account in the model, the impact of production scale on the total cost will be far more significant than will be shown in the following analysis. The following exponential function[6] is suggested to represent the network effect in the model.

$$oc = \exp\left[se \times \left(\frac{1-s}{t} - 1 \right) \right] \quad \text{--} \quad (2)$$

6) This function is modified from the network effect model of Sterman (2000)

where *oc* stands for the operating cost of AFVs relative to the operating cost of conventional cars, *se* for sensitivity of network effect, *s* for share of AFVs in sold car stock and *t* represent threshold for network effect.

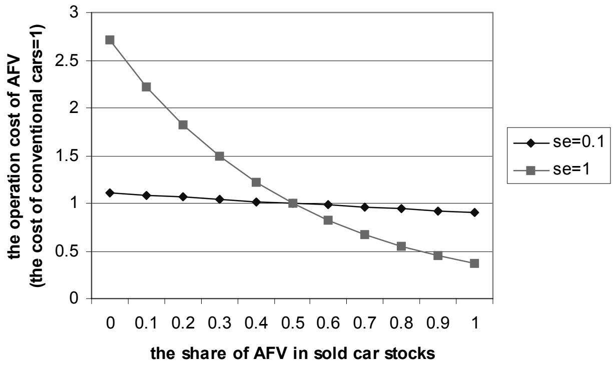

Figure 2 The sensitivity of network effect in the model

Figure 2 illustrates the degrees of network effects according to different values of sensitivity parameter (se) in the model. The model assumes that t is equal to 0.5, that is, that the network effect is symmetrical to both types of cars. In the case of se=0.1 the network effect in operating cost is not significant. The overall relative cost of AFV changes in the region of about ±10% difference from the cost of conventional cars. Meanwhile, in the case of se=1, there is a significant network effect. The relativ eoperating cost of AFV changes from 2.7(the cost of conventional cars=1) to 0.37 as its share in total sold car stock changes from 0% to 100%.

Fourthly, the model introduces three key policy instruments to increase the market share of AFVs; subsidy on vehicles, subsidy on operating cost and niche market management[7]. It is assumed that by niche management policy the government can control a specific market share of vehicles regardless of the total cost of vehicles. For example, the government may have

7) Niche management policy for AFVs can be referred to in Farrell et al. (2003), Hoogma et al. (2002) and Kemp (1998).

control on the purchase of cars for the public service or fleet operation sector by voluntary agreements, financial incentives or regulations. It is assumed in the model that niche market policy can be introduced when the gap in vehicle production costs between conventional cars and AFVs is reduced to the 50% level. The subsidy policy is to reduce vehicle price or operating cost (fuel cost) of AFVs by a tax differentiation or direct subsidy.

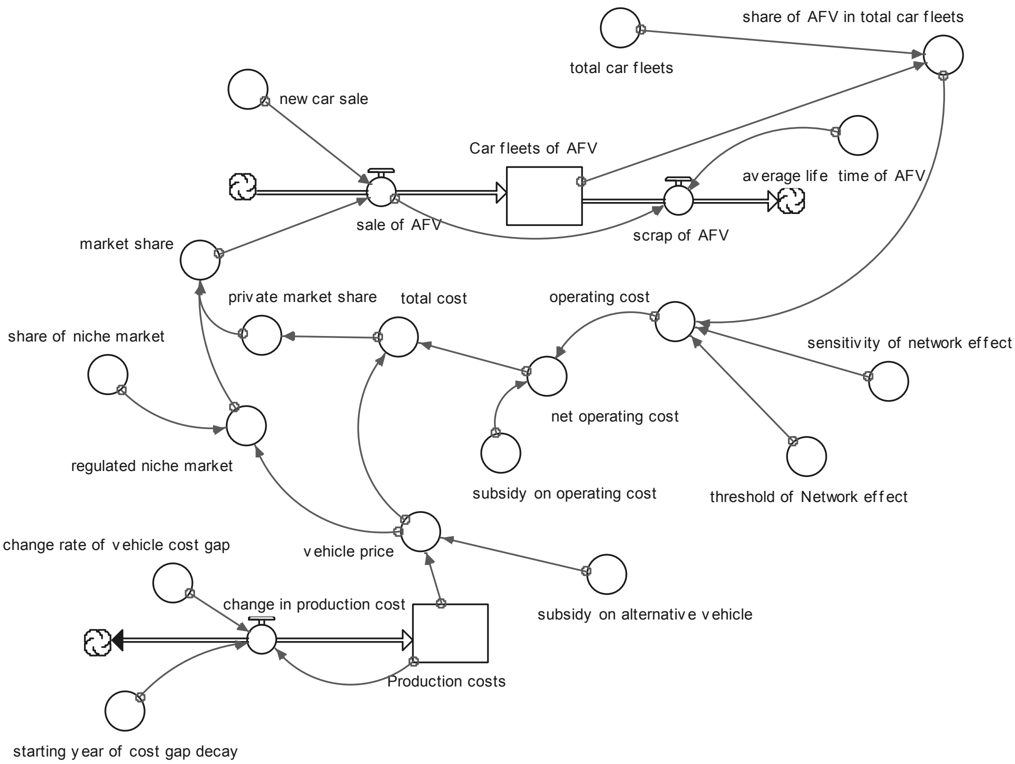

Figure 3 A system dynamics model of the market share of AFVs

Figure 3 illustrates a system dynamics model of the market share of AFVs. A rectangle in the figure stands for a stock variable. The value of a stock variable is controlled by flow variables, which are represented by pipelines in the figure. Other useful information determining the whole system behaviour is represented by converters, which have a circle shape. The arrows in the figure show the causal relationship of the whole system.

Ⅲ. Network Effect of Vehicle Operating Costs

Before the analysis of network effect of vehicle operating costs, this study first investigates a market situation where there is no significant network effect in vehicle operating costs. For example, figure 4 illustrates the change of market share and relative cost of AFVs when allowing only a small network effect by setting the sensitivity of the network effect to 0.1. Under this assumption, the operating cost of AFVs is only about 10% higher than that of conventional cars with a 0% share of sold car stocks and 10% lower with a 100% share (see also se = 0.1 in figure 2).

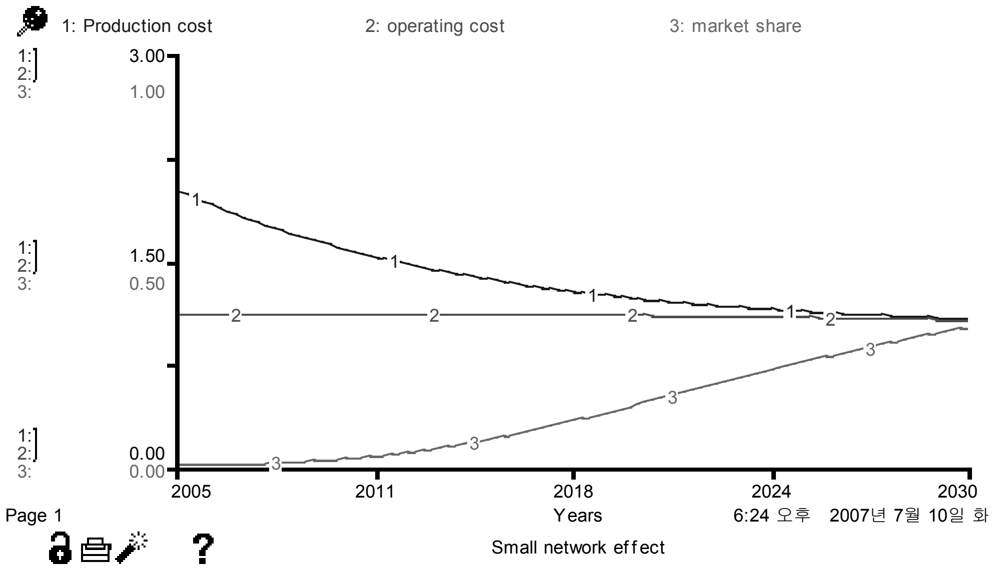

Figure 4 The market share and relative costs of AFVs when there is no significant network effect

As shown in figure 4[8], the market share of AFVs increases gradually over the simulation period and reaches 34% of the market share in 2030 without implementing any policy instrument. Vehicle production costs decrease annually by 10% as assumed in the model, and vehicle operating costs are not significantly affected by the market share. That is, if there is

8) As emphasised earlier, since the model of car market share is based on several hypothetical assumptions, more attention should be on the general model behaviour of market share rather than the precise figures of the model outcomes.

no significant network effect of the vehicle operating cost, the gradual rise of the market share of AFVs can be expected without a policy intervention.

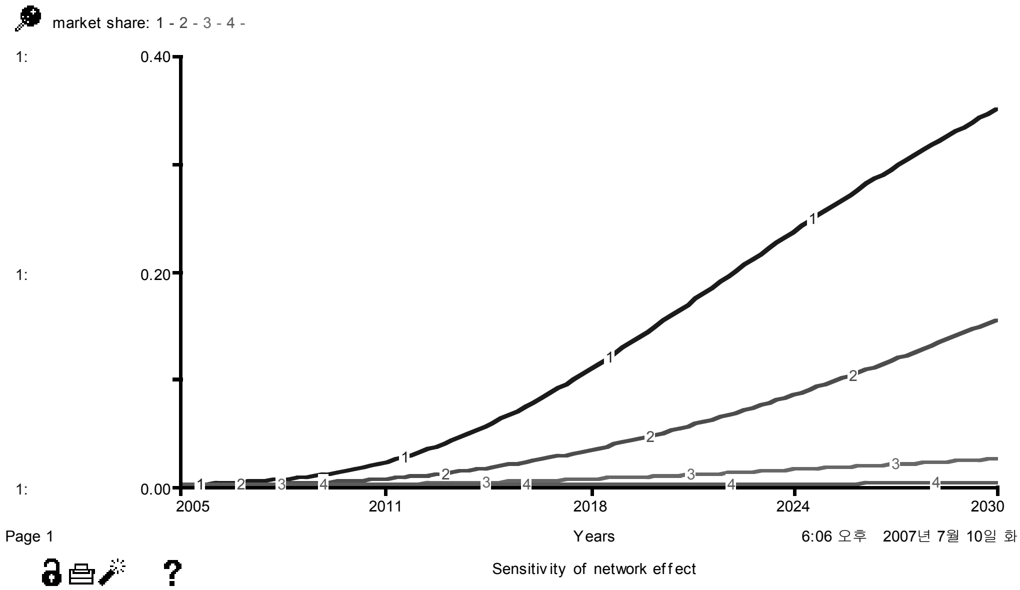

Figure 5 The change of the market share of AFVs under various network effects

However, if there is a significant network effect with regard to the operating cost of vehicles, the diffusion of AFVs in the market can be more difficult. For example, figure 5 illustrates changes in the market share of AFVs under varied scales of the network effect. It shows the changes in the market shares trends by setting the sensitivity parameter of network effect in the model into 0.1 (graph 1), 0.4 (graph2), 0.7(graph 3) and 1 (graph 4) respectively. The range of the relative operating cost is extended with a higher sensitivity parameter of network effect. With a sensitivity parameter of 0.1, the operating cost of AFVs changes in the range of about a 10% difference from that of conventional cars. The range is extended to about 50%, 100% and 270% with a sensitivity parameter of 0.4, 0.7 and 1 respectively. As shown in the figure, as the network effect is assumed to be more significant, the rise of market share of AFVs is more limited. In fact, with a sensitivity of network effect of 1 in the model, the sales of AFVs experience little increase over the whole simulation period.

It is not that all types of AFVs have a similar network effect in operating cost. For example, the operating cost of hybrid cars that use conventional fuels as well as an electric battery will have relatively little dependence on the scale of sold vehicle stock. Therefore, for these types of AFVs it will be less difficult to increase the market share without strong government intervention (trends 1 or 2 in figure 5) as long as vehicle production costs fall to a similar level as those of conventional cars. However, AFVs which require a separate fuel supply infrastructure from conventional cars (e.g. hydrogen fuel cell cars) will have a significant network effect because fuel supply (access) cost will vary significantly according to the scale of vehicle stock. For these types of AFVs, it will be difficult to raise market shares (trend 3 or 4 in figure 5). In what follows, this study focuses on the latter types of AFVs.

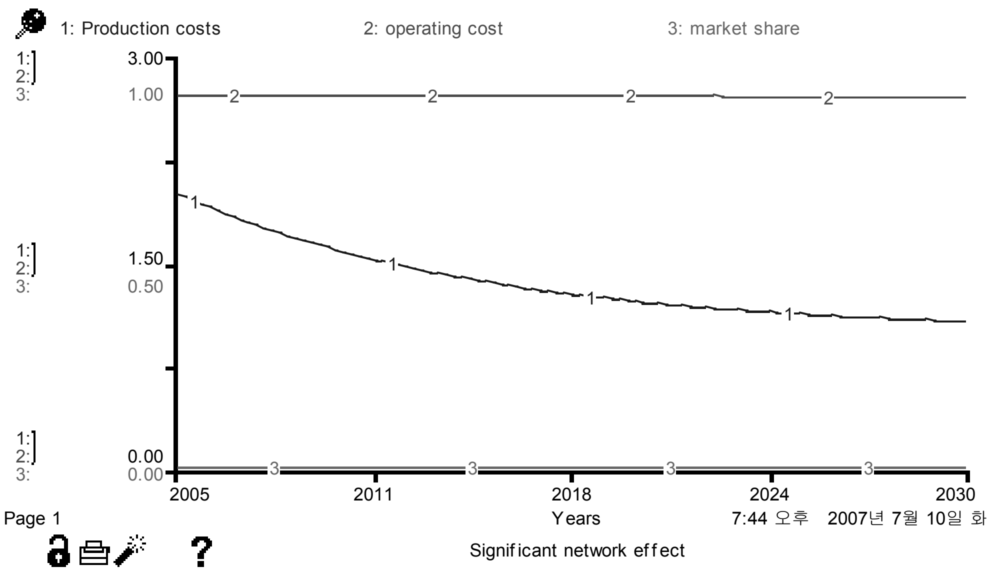

Figure 6 The market share and relative costs of AFVs when there is a significant network effect

Figure 6 illustrates the change of the market share and relative cost of AFVs for case 4 in figure 5, where there is a significant network effect on the operating cost of vehicles (sensitivity =1). As shown in the figure, under this assumption the market share of AFVs cannot rise at all due to the high operating cost of AFVs. The operating cost of AFVs does not decrease because of a very low market share. There is a vicious circle between the low sales of AFVs and the high operating cost. The vehicle market is locked in its current structure. Consumers do not buy AFVs because the operating cost of AFVs is too high not only in terms of monetary cost but also in terms of accessibility to fuel as well as in terms of reliability of car maintenance. Fuel suppliers and car manufacturers also fail to reduce fuel supply costs and vehicle service costs owing to the small stock of AFVs. There are increasing returns to scale for the fuel supply sector and vehicle maintenance sector.

Ⅳ. The Impact of Various Policy Instruments on the Market Trends of AFVs

In the previous analysis the simulation result showed that if there is a significant network effect on vehicle operating costs, the vehicle market could be locked in its current structure, resulting in little rise of AFV sales. Now this study turns to the possible policy instruments to break the vicious circle between low sales of AFVs and their high operating costs and to substantially increase the market share of AFVs. The model focuses on three policy instruments; a subsidy on vehicles, a subsidy on operating costs and the use of a niche market.

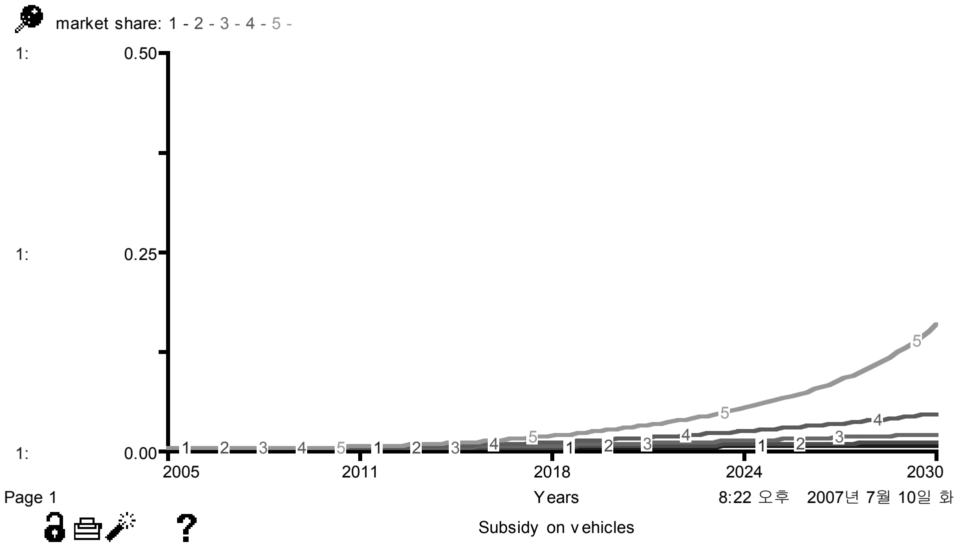

Figure 7 The market share of AFVs under subsidies on the purchase of AFVs

However, this observation is based on the view that there is continuity in technology development. In other words, it is conditional on the assumption that development of AFVs with less of a network effect (e.g. hybrid cars) will also stimulate development of AFVs with a significant network effect (e.g. hydrogen fuel cell cars) that have more environmental benefit in the long term. However, if there is not a similarity to a significant extent in technology development for both types of AFVs, it may be sensible to support the more environmentally beneficial AFVs from the outset in spite of the market barriers arising from the significant network effect. Of course, if AFVs which rely on the fuel supply infrastructure of conventional cars have more long-term benefit as well as short-term benefit than AFVs which require a fundamentally different fuel supply infrastructure from conventional cars (or there is little difference between them), policy efforts to support the former type of AFVs (e.g. hybrid cars) rather than the latter type of AFVs (e.g. hydrogen fuel cell cars) could be justified straightforwardly

First, figure 7 compares the market share of AFVs when varied amounts of subsidy are given to the purchase of AFVs. Graph 1 represents the trend of the market share of AFVs under a 10% (of conventional car price) subsidy and trends 2, 3, 4, and 5 represent the trend under 20%, 30%, 40% and 50% subsidies respectively. As illustrated in the figure, the varied outcomes are ranked in accordance to the amount of the subsidy. Even a 40% subsidy on vehicle price fails to substantially increase the market share of AFVs over the whole simulation period (2005-2030). Only a subsidy of 50% manages to substantially increase the market share of AFVs, - up to 16%.

Next, figure 8 compares the market share of AFVs when varied amounts of subsidy are given to the operating cost (fuel cost) of AFVs. Graph 1 represents the trend of the market share of AFVs under a 20% (of the fuel cost of conventional cars) subsidy and trends 2,3,4, and 5 represent the trend under 40%, 60%, 80% and 100% subsidies respectively. The result is the same as the subsidy on vehicles in figure 7. Even a 80% subsidy on operating costs fails to substantially increase the market share of AFVs. Only a subsidy of 100% manages to substantially increase the market share of AFVs, - up to 16%. Since the vehicle price has twice as much weight as operating costs in calculating the total cost of vehicles in the model, a twice as high subsidy rate on fuel is required to lead to the same result as the vehicles' subsidy policy.

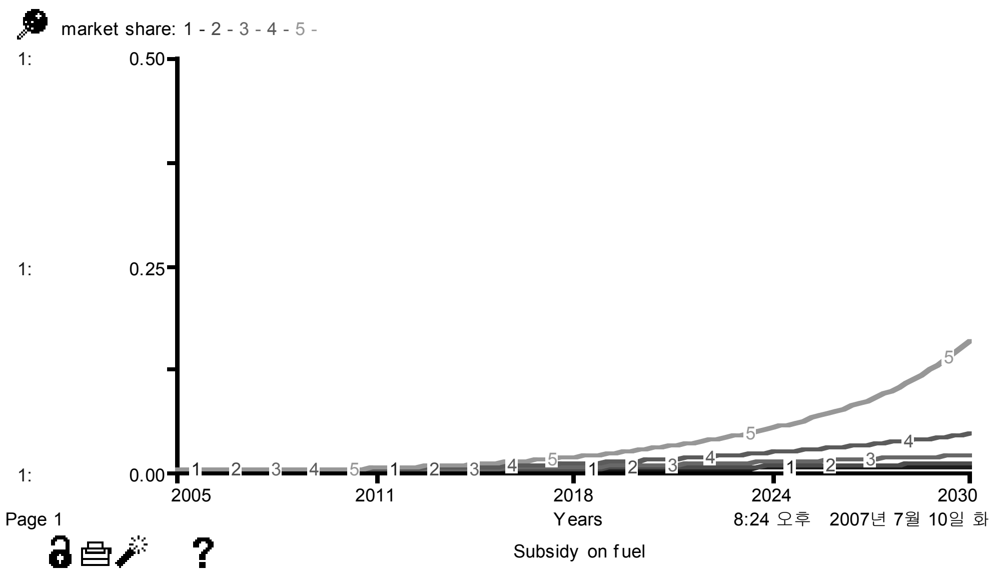

Figure 8 The market share of AFVs under subsidies on fuel (operating cost) of AFVs

Another policy instrument to be investigated in the model is a niche management policy. Here it is assumed that the government can control a specific niche market such as vehicles for the public service or vehicles of fleet operators. The model assumes that the whole niche market of new cars shifts to AFVs when the vehicle production cost of AFVs falls to less than 50% above that of conventional cars. Figure 9 illustrates changes in the market share of alternatives cars according to the varied scales of niche markets. Graph 1 illustrates the change of market share under 1% niche market management and graph 2 and 3 show the trends under 3% and 5% niche market respectively. As illustrated in the figure, niche management policy alone fails to sustain the rise of the market share of AFVs in any scenario.

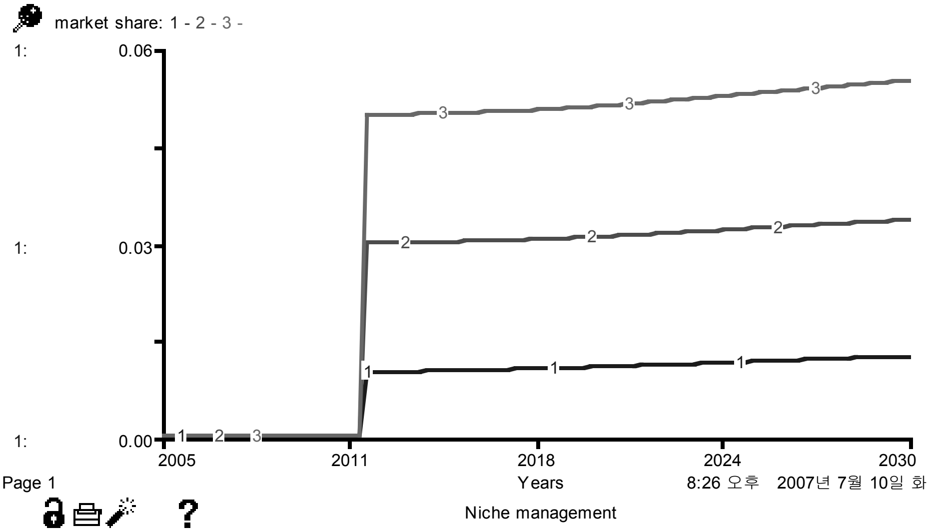

Figure 9 The market share of AFVs under the niche market policy

To summarise the results above, a subsidy policy on either vehicles or fuel (operating cost) could be effective to break the 'locked in' market structure and to increase the market share of AFVs under the assumption of a significant network effect on the operating cost of vehicles. However, a substantial rise of the market share of AFVs requires an extremely high subsidy; about a 50% vehicle subsidy or a 100% fuel subsidy of the cost of conventional cars under the assumptions of this model. In addition, it was found from the previous analysis that niche management policy alone is not effective in increasing the sales of AFVs substantially. Now this study turns to the combined effect of policy instruments. First, figure 10 shows the simulation result under a 25% vehicle subsidy and a 50% fuel (operating cost) subsidy. As illustrated in the figure, the market share of AFVs increases significantly, up to 16%. The operating cost of AFVs falls substantially as its market share grows gradually although it is still much higher than that of conventional cars even at the end of the simulation period.

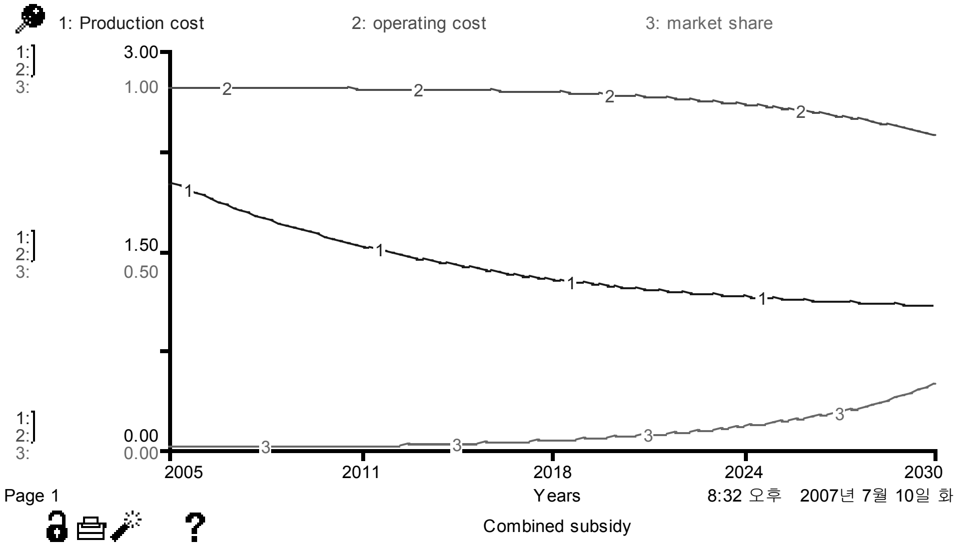

Figure 10 The market share of AFV under subsidies on vehicle and fuel

Figure 11 shows the simulation result under the same subsidy policies as figure 10 and niche management policy (2% market share). As illustrated in the figure, this combination of policies increases the market share of AFVs dramatically up to 39%. Although niche management policy had little impact when applied alone under the assumption of a considerable network effect on the operating cost of vehicles, it is clearly effective in advancing the realisation of the impact of the other policy instruments.

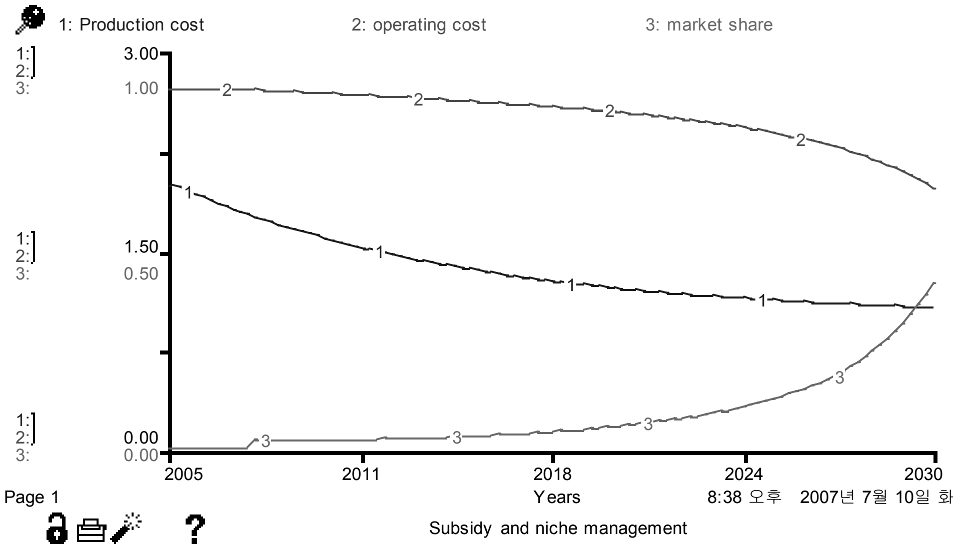

Figure 11 The market share of AFVs under subsidies and niche market policies

Ⅴ. Conclusion

If there is a significant network effect for vehicle operating costs, it would be difficult to achieve the shift to AFVs even in the long term without a strong policy intervention because the car market is locked in to its current structure. Network effects can be caused by increasing returns to scale in the fuel supply sector as well as in the maintenance service sector. They are also related to the fact that the reliability and awareness of consumers of new products increases with the growth of the market share of the new products. AFVs which rely on the fuel supply infrastructure of conventional cars such as hybrid cars should have less of a network effect for operating costs. These vehicles would have less difficulty in increasing their market share than AFVs which require a fundamentally different fuel supply infrastructure from conventional cars (e.g. hydrogen fuel cell cars). Therefore it could be effective to put a policy focus on the former type of AFVs (with less of a network effect: same fuel supply infrastructure as conventional cars) even if the latter type of AFVs (with a significant network effect: different fuel supply infrastructure from conventional cars) have more environmental benefit in the long term, by the time the cost gap between conventional cars and AFVs decreases substantially.

However, this observation is based on the view that there is continuity in technology development. In other words, it is conditional on the assumption that development of AFVs with less of a network effect (e.g. hybrid cars) will also stimulate development of AFVs with a significant network effect (e.g. hydrogen fuel cell cars) that have more environmental benefit in the long term. However, if there is not a similarity to a significant extent in technology development for both types of AFVs, it may be sensible to support the more environmentally beneficial AFVs from the outset in spite of the market barriers arising from the significant network effect. Of course, if AFVs which rely on the fuel supply infrastructure of conventional cars have more long-term benefit as well as short-term benefit than AFVs which require a fundamentally different fuel supply infrastructure from conventional cars (or there is little difference between them), policy efforts to support the former type of AFVs (e.g. hybrid cars) rather than the latter type of AFVs (e.g. hydrogen fuel cell cars) could be justified straightforwardly[9)].

There are several possible policy options to break the 'locked in' structure of the car market when there is a significant network effect, such as a subsidy on vehicle price (capital cost), subsidy on fuel (operating cost) and niche management policy. The level of subsidy required to break the 'locked in' market structure will depend on the extent of the network effect, but it is likely to be substantial. Combined policy options would be more effective than relying on a single policy option to increase the market share of AFVs.

9) However, hydrogen fuel cell cars are generally regarded as having long-term benefit than other types of AFVs although there is still much uncertainty on future technology changes of AFVs.

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