# Building a market share model of Alternative Fuel Vehicles: from generic system archetypes to system dynamics modelling

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Abstract

*This study investigates the market barriers in increasing the market share of Alternative Fuel Vehicles (AFVs). In particular, this study first conceptualises the AFVs market model by aid of generic system archetypes suggested by Wolstenhome. Among four generic system archetypes suggested by Wolstenhome, the market structure of AFVs can be explained by the 'relative achievement' archetype. Starting from the generic system archetype, this study extends the model boundary step by step to take account of various model assumptions necessary to simulate the model numerically. If there is a significant network effect on vehicle operating costs, it is difficult to achieve the shift to AFVs even in the long term without a policy intervention because the car market is locked in to the current structure. 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.*

Key words

Generic system archetype, Relative achievement, Lock-in, Increasing return to scale, Network effect, Alternative Fuel Vehicles

## 1. Introduction

Alternative Fuel Vehicles (AFVs) such as electricity, hybrid, bio-fuels and fuel cell vehicles have potential to remarkably reduce $CO_2$ 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 fossil 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.

The model building process in this paper is based on generic system archetypes suggested by Wolstenhome (2003, 2004). In section 2, this paper first explains the generic system archetype of Wolstenhome (2003, 2004) and examines which archetype is best suited to describe the AFV market structure. Then, it builds a system dynamics model on the basis of the generic system archetype to numerically simulate the AFV market behaviours under various scenarios. The modeling process is a stepwise extension of model boundary, starting a direct transformation of the generic system archetype into a stock flow model. 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 given in the model. 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 section 3, the focus of the analysis moves into policy simulations and this paper suggests some possible policy options to overcome the market barriers found in section 2. Solution archetypes of Wolstenholme are also examined in section 3.

## 2. Building a system dynamics model of the AFVs market

### 2.1 A generic system archetype for the model

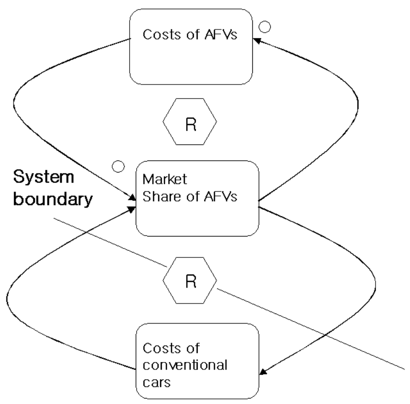
Wolstenholme (2003, 2004) suggested that generic system archetypes can be useful as free standing devices to aid model conceptualisation and as means of disseminating insights arising form models. This paper also attempts to build a system dynamics model of AFVs market shares by an aid of generic system archetypes suggested by Wolstenholme. The key characteristics of the archetypes suggested by Wolstenholme (2003, p.10) are as follows; first, 'an *intended consequence (ic) feedback loop* which results from an action initiated in one sector of an organisation', second, 'an unintended consequence feedback loop which results from a reaction within another sector of the organisation or outside', third, 'a delay before the unintended consequence manifest itself', fourth, 'an organisational boundary that hides the unintended consequence from the view of those instigating the intended consequences, fifth 'that for every problem archetype, there is a solution archetype'.

According to Wolstenholme (2003, 2004) there are four generic system archetypes consisting of the four ways of ordering a pair of reinforcing and balancing feedback loops. Those are named by Wolstenholme (2003, p.11) as: first, 'u*nderachievement*, where intended achievement fails to be realised', second, 'out of control, where intended control fails to be realised', third, 'r*elative achievement*, where achievement is only gained at the expense of another', fourth, 'r*elative control*, where control is only gained at the expense of others'.

Among four generic system archetypes above, the market structure of AFVs and conventional cars can be explained by 'relative achievement', where the *ic* loop and the *uc* loop are reinforcing loops. As shown in figure 1, there are reinforcing feedback loops between operating costs and the market share for each car types. The positive feedback relationship between operating costs and the market shares is due to a 'network effect' or 'increasing returns to scale' for vehicle operating 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 (Kwon, 2007). 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.

Figure 1 The 'Relative achievement' archetype for car market shares




R= reinforcing feedback loop; o = opposing action

The key concepts 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) provides a reference model for system dynamics modelling of increasing returns to scale and path dependence.

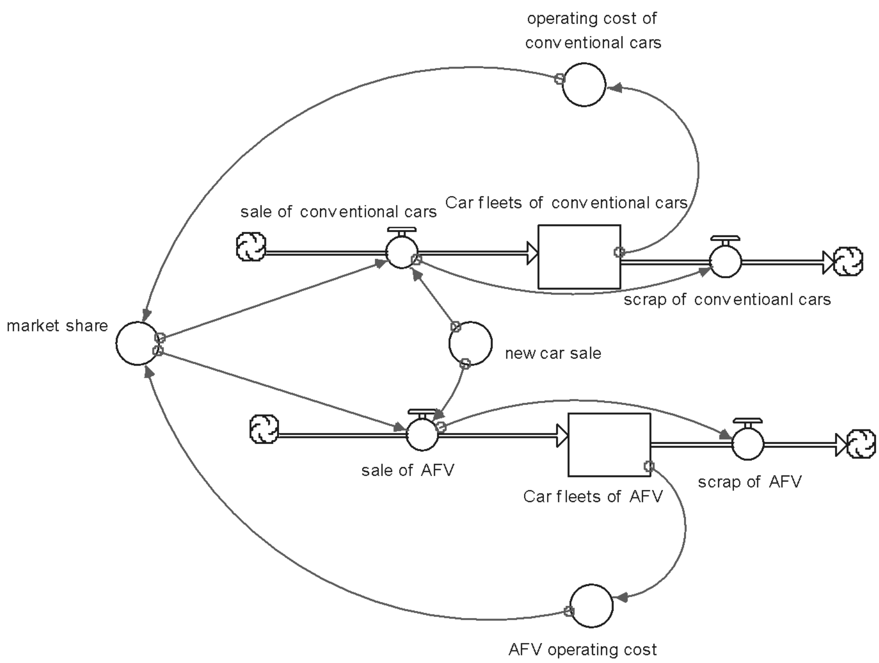
In a 'relative achievement' archetype, 'achievement is gained at the expense of other sectors of the organisation. The net effect is that unintended consequence works to the benefit of the *ic* loop and magnifies the relative outcome (Wolstenholme, 2003, p.12).' That is, the market advantage of one type of cars (e.g. conventional cars) is gained at the expense of the other type of car (e.g. AFVs) and the reinforcing feedback loops magnifies the relative advantage of conventional cars in the system.

Though the generic causal loop structure shown above is very useful in conceptualising system behaviours of car markets, a numerical model is needed to investigate system behaviours of AFV market shares under various market conditions and to examine effects of policy intervention. In the next section, we build a system dynamics model of AFVs car market share, starting from the generic system archetype explained in this section.

2.2 Building a system dynamics model from generic system archetypes

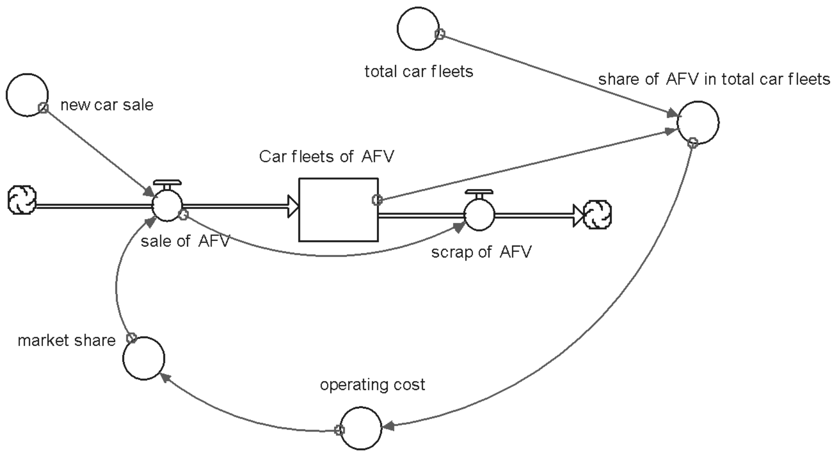
The operating cost of each type of car has positive feedback with its market shares as revealed in the previous section. Although vehicle production costs can also be regarded as having a positive feedback relationship with the market shares in a similar manner to operating cost, this is not considered 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 domestic 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. Figure 2 illustrates a system dynamics model of car market shares, which is a direct transformation of the generic system archetype in figure 1 into a stock-flow model. Car fleets are incorporated as stock variables into the system dynamics model.

Figure 2 A system dynamics model of the 'Relative achievement' archetype of car market shares




Since there are only two types of cars in the model, if a market share of one type of cars is determined, that of the other type is also determined. Thus it is sufficient to include only one type of cars in order to simulate the whole car market structure, leaving only one reinforcing loop in the model. All cost variables are represented as relative values in a single loop model. Figure 3 illustrates a system dynamics model of cars market shares, focusing on AFVs market share alone.

Figure 3 A system dynamics model focusing on the AFVs market shares




## 2.3 The Additional assumptions for numerical simulations of the AFVs market model[1]

Additional assumptions are needed to simulate the AFVs market model numerically. 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[2]. 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.

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

where m is the market share of AFVs, c is the relative total cost of AFVs (the cost of conventional cars =1)[3], and α and β are parameters determining the location and slope of the logistic curve respectively.

Since it is not possible to empirically estimate α and β, 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[4]. 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

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[1] This part is based on Kwon (2007)
[2] 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.
[3] That is, c = the total cost of AFVs / the total cost of conventional cars
[4] When m(c) = 0.5 = 1/[1+exp(α + β×1)] in equation (2.2), as exp(0) = 1, α + β must equal 0 (Cramer, 1991).

the total car fleets have constant values over time in the model. The initial value of AFV car stocks is 0 in the model.

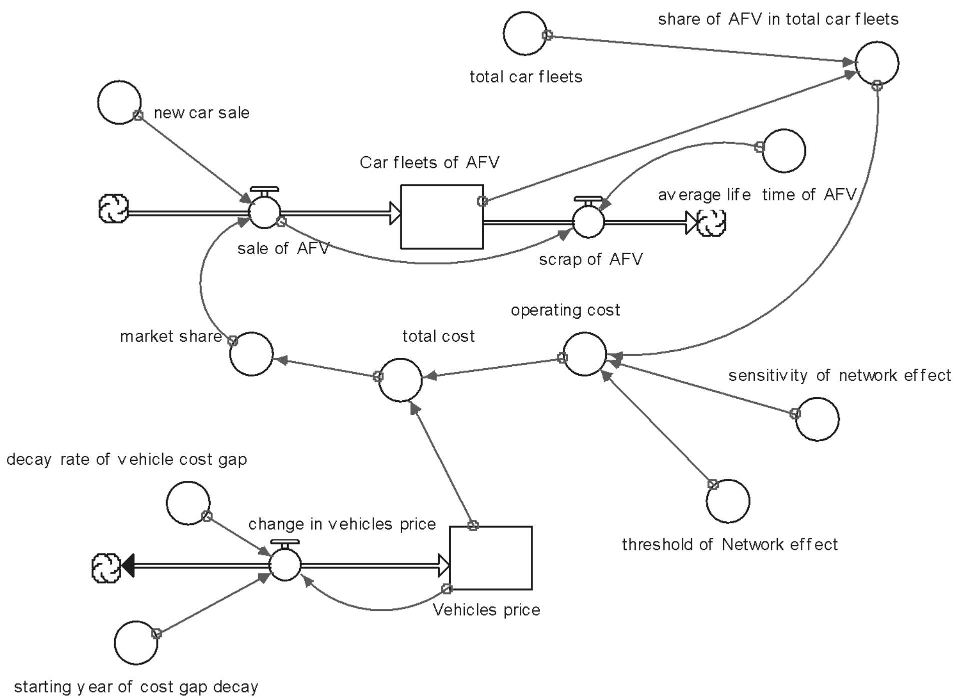
Secondly, the relative price of AFVs is assumed to be twice as high as the vehicle price of conventional cars at the initial year of the simulation period. Then it is assumed that the gap of production cost between the two types of cars declines annually by 10%.

Thirdly, to represent the network effect, the following exponential function[5] is suggested in the model.

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

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 4 The system dynamics model of the AFVs market share including additional assumptions




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 relative operating 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%.

[5] This function is modified from the network effect model of Sterman (2000)

There are additional assumptions of the model which are not critical in determining system behaviours of the models. The model assumes 12 years of average life time of cars and fifth-order delay function for cars scrap. The simulation period is set to 30 years. Figure 4 illustrates the AFVs market model incorporating all these additional assumptions. The model listing is provided in the end of the paper.

2.4 Simulations of the network effect of vehicle operating costs

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. 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.

Figure 5 Changes in market shares of AFVs under various network effects

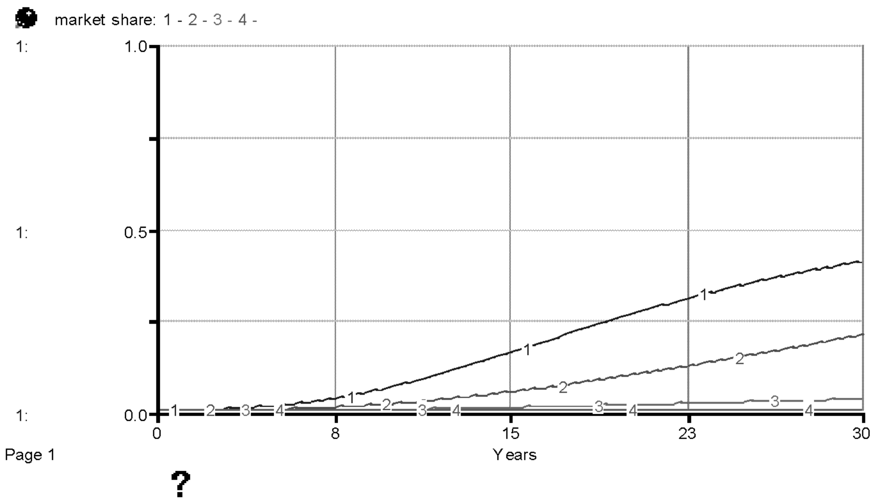



Figure 5 illustrates changes in the market share of AFVs under varied scales of the network effect. It shows the changes in the market shares trends by setting the sensitivity parameter of network effect in the model into 0.01 (graph 1), 0.34 (graph2), 0.67(graph 3) and 1 (graph 4) respectively. The range of the relative operating cost is extended with a higher sensitivity parameter of network effect (Kwon, 2007). 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. Under a significant network effect like graph 4, 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 is increasing returns to scale for the fuel supply sector and vehicle maintenance sector.

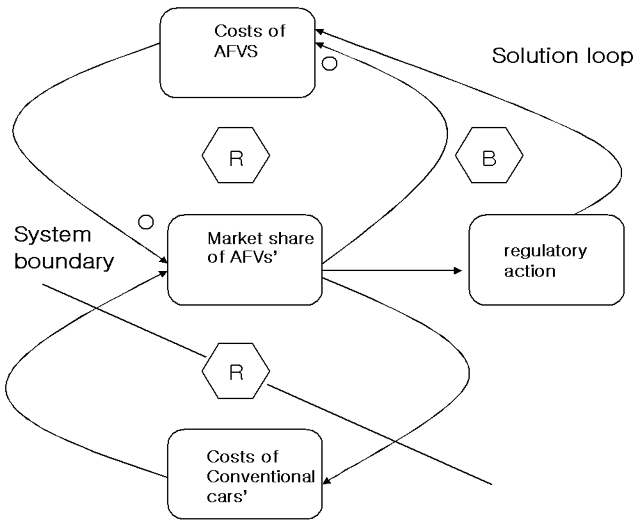
If there is little network effect of the vehicle operating cost, the gradual rise of the market share of AFVs can be expected without a policy intervention as long as vehicle production costs fall to a similar level as those of conventional cars(trends 1 or 2 in figure 5). However, if there is a significant network effect with regard to the operating cost of vehicles, the diffusion of AFVs in the market can be more difficult(trend 3 or 4 in figure 5). In what follows, this study focuses on the latter types of AFVs.

## 3. Policy simulation to increase the market share of AFVs

### 3.1 Building policy models to increase the market share of AFVs

As mentioned in section 2, Wolstenholme (2003, 2004) provided solution archetypes as well as problem archetypes for all four types of general two-loops system archetypes. According to Wolstenholme (2003, p.13), a possible solution to the relative achievement archetype is to define 'a new balancing feedback loop by which to control a more equitable transition to a new state, perhaps by external regulation.' Figure 6 shows a solution archetype for the AFVs market model based on Wolstenholme (2003, 2004). That is, to break the vicious circle between low market shares and high operating costs for AFVs, the system requires some regulatory actions, which can reduce cost of AFVs even under low market shares of AFVs. This study investigates the effects of subsidies and niche management policy as regulatory actions to break a 'locked-in' market structure. One difference from Wolstenholme's generic solution archetypes is that policy options in this paper are introduced as external factors rather than as constituting balancing loops, in order to compare the effects of various policy options.

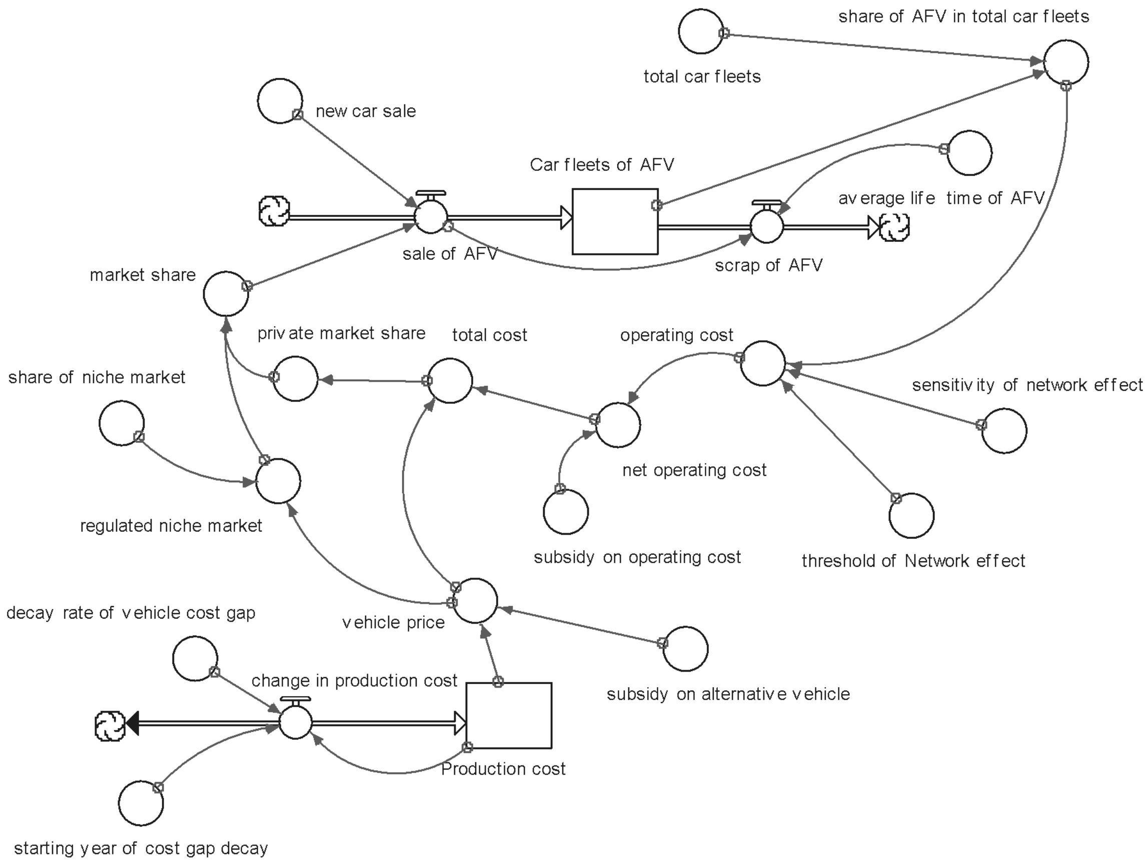
Figure 6 The solution archetype for the AFVs market model




R= reinforcing feedback loop; B= balancing Feedback loop; o = opposing action

The model introduces three key policy instruments to increase the market share of AFVs; subsidies on vehicles, subsidies on operating cost and niche market management[6]. 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 control on the purchase of cars for the public service or fleet operation sector by voluntary agreements, financial incentives or regulations. Niche market policy is introduced when the gap in vehicle production costs between conventional cars and AFVs is reduced to the 50% level in the model. The subsidy policy is to reduce vehicle price or operating cost (fuel cost) of AFVs by a tax differentiation or direct subsidy. Figure 7 shows the system dynamics model of AFVs market shares incorporating policies intervention.

Figure 7 A system dynamics model of the market share of AFVs incorporating policies intervention



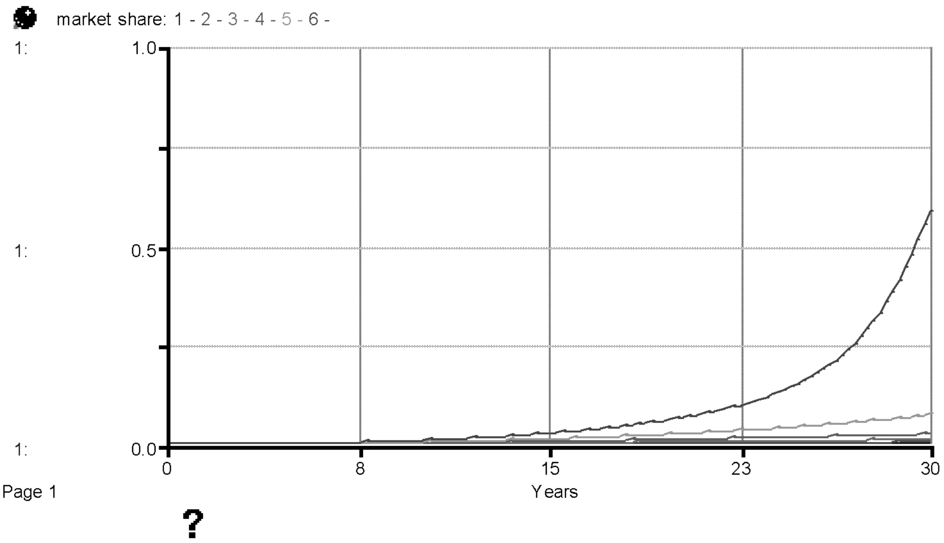

## 3.3 The effects of policies intervention to increase the market share of AFVs

Figure 8 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 with no subsidy and graph 2, 3, 4, 5 and 6 represents the trend under 10%, 20%, 30%,

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

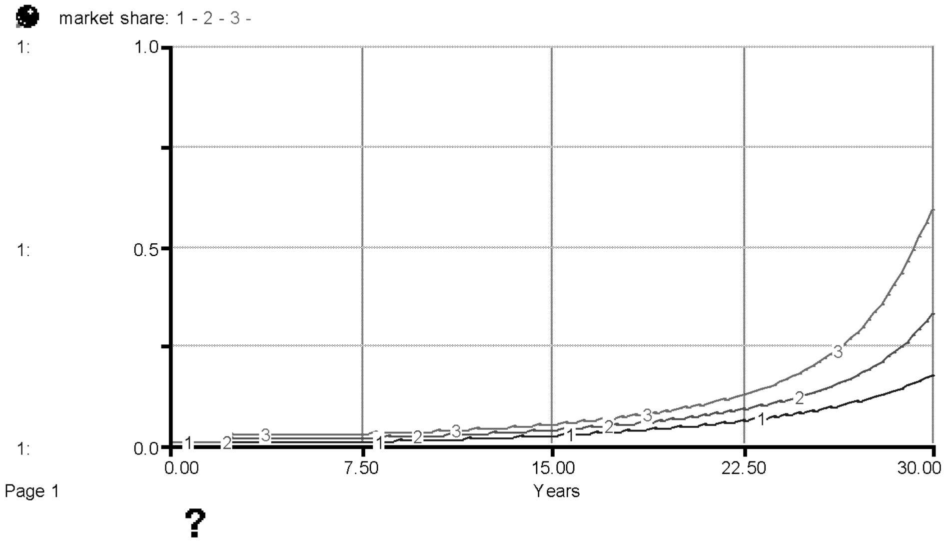
40% and 50% subsidies (of conventional cars) respectively. As illustrated in the figure, the varied outcomes are ranked in accordance to the amount of the subsidy. Even a 40% subsidy on vehicle price fails to substantially increase the market share of AFVs over the whole simulation period. Only a subsidy of 50% manages to substantially increase the market share of AFVs, - up to 59%. 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. That is, 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 59%.

Figure 8 The market share of AFVs under subsidy policies




Now this study turns to the combined effect of policy instruments. First, graph 1 in figure 9 shows the simulation result under a 30% vehicle subsidy and a 30% fuel (operating cost) subsidy combined without niche management policy. As illustrated in the figure, the market share of AFVs increases, up to 17% over 30 years. Graph 2 and graph 3 in figure 9 reveal the impact of the subsidy polices as well as of niche management policy combined, respectively representing 1% and 2% niche markets. 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. As illustrated in the figure, this combination of policies increases the market share of AFVs dramatically up to 32% (30% subsidies and 1% niche market policy combined) and 59% (30% subsidies and 2% niche market policy combined).

Figure 9 The market share of AFVs under combined policies (30% subsidies and niche management policy)




4. Conclusion

This study investigated 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, the system dynamics model of AFVs market share of this study was first conceptualised by aid of generic system archetypes suggested by Wolstenhome (2003, 2004). In fact, the modeling process in this paper is a stepwise extension of model boundary, starting a direct transformation of the generic system archetype into a stock flow model. Among four generic system archetypes suggested by Wolstenhome (2003, 2004), the market structure of AFVs can be explained by 'relative achievement', where the *ic* loop and the *uc* loop are reinforcing loops because there are reinforcing feedback loops between operating costs and the scale of car stock for each car types. The positive feedback relationship between operating costs and the scale of car stocks is due to a 'net work effect' for vehicle operating cost.

According to the simulation results, 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.

A solution to the relative achievement archetype is to define 'a new balancing feedback loop by which to control a more equitable transition to a new state, perhaps by external regulation.'(Wolstenholme, 2003, p.13). That is, to break the vicious circle between low market shares and high operating costs for AFVs, the system requires some regulatory actions, which can reduce cost of AFVs even under low market shares of AFVs. There are several possible policy options to break the 'locked in' structure of the car market 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.

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<Model listing>

Car_fleets_of_AFV(t) = Car_fleets_of_AFV(t - dt) + (sale_of_AFV - scrap_of_AFV) * dt
INIT Car_fleets_of_AFV = 0
INFLOWS:

sale_of_AFV = new_car_sale*market_share
OUTFLOWS:
scrap_of_AFV = SMTHN(sale_of_AFV,average_life__time_of_AFV,5,0)
Production_cost(t) = Production_cost(t - dt) + (change_in_production_cost) * dt
INIT Production_cost = 2
INFLOWS:
change_in_production_cost = IF (TIME >= starting_year_of_cost_gap_decay) THEN ((Production_cost-1)*decay_rate_of_vehicle_cost_gap) ELSE 0
average_life__time_of_AFV = 12
decay_rate_of_vehicle_cost_gap = CGROWTH(-10)
market_share = regulated_niche_market+private_market_share*(1-regulated_niche_market)
net_operating_cost = operating_cost-subsidy_on_operating_cost
new_car_sale = 1000000
operating_cost = EXP(sensitivity_of_network_effect*((1-share_of_AFV_in_total_car_fleets)/threshold_of_Network_effect-1))
private_market_share = 1/(1+EXP(10*(total_cost-1)))
regulated_niche_market = IF(vehicle_price < 1.5) THEN(share_of_niche_market) ELSE(0)
sensitivity_of_network_effect = 1
share_of_AFV_in_total_car_fleets = Car_fleets_of_AFV/total_car_fleets
share_of_niche_market = 0
starting_year_of_cost_gap_decay = 0
subsidy_on_alternative_vehicle = 0
subsidy_on_operating_cost = 0
threshold_of_Network_effect = 0.5
total_car_fleets = 10000000
total_cost = 1/3*net_operating_cost+2/3*vehicle_price
vehicle_price = Production_cost-subsidy_on_alternative_vehicle