HÁSKÓLINN Í REYKJAVÍK
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Exploring the Diffusion of Alternative Fuel Vehicles in Iceland using System Dynamics Simulation

Lilja Björg Guðmundsdóttir

Thesis of 30 ETCS credits
Master of Science in Engineering Management

June 2016

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Thesis of 30 ECTS credits submitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment of
the requirements for the degree of
Master of Science in **Engineering Management**

June 2016

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Abstract

In this paper we present a simulation model that was made for the United States but has been adjusted to Icelandic situation. The model captures the coevolution of alternative fuel vehicles and corresponding refueling infrastructure. The emissions from road transport and possible emission reduction was explored along with associated cost. The possible emission reduction was explored through scenarios where different alternative fuel vehicles are subsidized. Results imply that incentives for alternative fuel vehicles and their corresponding infrastructure could help reduce emission from the transport sector. The results also suggest that offering incentives for all available alternative fuel vehicles reduces emission fastest but offering incentives for only battery electric vehicles is the cheapest way of reducing emissions.

Rannsókn á innleiðing vistvænna bíla á Íslandi með notkun kviks kerfislíkans

Lilja Björg Guðmundsdóttir

Júní 2016

Útdráttur

Í þessari ritgerð er kynnt hermunarlíkan sem var upphaflega gert fyrir Bandaríkin en hefur verið aðlagað að íslenskum aðstæðum. Líkanið nær utan um hvernig vistvænir bílar og samsvarandi eldsneytisstöðvar þróast saman. Útblástur frá vegasamgöngum var rannsakaður með uppsetningu á nokkrum sviðsmyndum í líkaninu þar sem mismunandi tegundir vistvænna bíla eru styrktir til að auka hlut þeirra í bifreiðaflotanum. Niðurstöður benda til þess að styrkir/hvatar geta hjálpað til við að draga úr útblæstri. Einnig benda niðurstöður til þess að með því að bjóða styrki/hvata til allra tegunda vistvænna bíla geti dregið mest úr útblæstri en ódýrast væri að styrkja einungis rafmagnsbíla.

I dedicate this thesis to my son, Arnar Valur Friðriksson

All models are wrong, but some are useful

-George Box

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First of all I wold like to thank my instructors, Eyjólfur Ingi Ásgeirsson and Hlynur Stefánsson for helping me with this project. They have both participated in various ways and their support is of great value.
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Chapter 1

Introduction

Since the first gasoline vehicle was introduced in the late 19th century, technology has evolved. The number of vehicles per capita has grown along side of GDP while new and better technology has enabled people to travel longer distances than before. These growths, along with the fact that fossil fuel has been the dominant energy source, have the effect that emission of greenhouse gases have increased considerably. Those effects have negative impact on our environment and it is important to react and reduce these emissions. In the past years people have become more aware of these negative effects and that is partly why vehicle manufacturers have been developing vehicles with better fuel utilization and less emissions. They have also introduced vehicles that use alternative fuel such as electricity, hydrogen and biofuels. Diffusion of alternative fuel vehicles (AFV) has been limited, partially because they are usually more expensive than gasoline and diesel vehicles and because of lack of charging/refueling infrastructure. The refueling infrastructure grows slowly after the introduction of a vehicle platform since fuel providers have little interest in investing in pumps/charging points for a platform with few vehicles. Therefore it takes time for the platform fleet and infrastructure to coevolve together, known as the chicken and egg problem.

This is no different in Iceland. When new AFV platforms are introduced, the lack of fuel infrastructure has limited the diffusion. Several different types of fuel for vehicles are available in Iceland but, excluding gasoline and diesel, there are very few refill pumps, for example there are only ten electric charging stations [1] and only 5 methane stations and most of them are in the same region [2]. The government is aware of the need to reduce emissions and have put forth policies to encourage people to buy vehicles with low emission. There are for example no excise taxes on vehicles with emissions less than 80 gr/km [3]. City council in the capital city of Iceland has also put forth policies for vehicles with low emission rate. Vehicles who emit less than 100 gr/km get free parking for 90 minutes in the capital city of Iceland [4]. The policies to support AFVs are set to support those who want to buy vehicles that have low emission rates. Howewer these incentives also applie to gasoline and diesel vehicles with low emission rates. These incentives are therefore not directly aimed at making way for AFV to reduce emission radically in the transport sector.

The task of increasing the AFVs part in the transport section is difficult due to the fact that there are many variables that affect peoples decision to buy an AFV. First of all the fossil fuel vehicles have established a certain niche in peoples minds but also because of little knowledge of AFVs, lack of fuel infrastructure and uncertainty in fuel supply. Attempts to introduce and encourage the diffusion of AFVs have been made over the world and some have failed, e.g. the introduction of CNG vehicles in Argentina [5]. Other attempts have been successful e.g. in Norway the introduction of electric vehicles has exceeded expectations [6].

Researchers have, over the past years, increasingly been studying the diffusion of AFVs and often simulation models are used to understand the diffusion system. Gnann and Plötz [7] point out that many researchers have studied the diffusion of AFVs and that some researchers suggest that AFVs and their infrastructure need to coevolve together while others suggest that an initial number of refueling stations is needed to jumpstart the diffusion. On the other hand, Zhao and Ma [8], who used an Agent Based simulation model to explore the diffusion system, say that the initial number of refueling stations should not be too high, because that could lead the refueling stations not surviving due to lack of customers.

The diffusion of AFVs in Iceland is interesting. The electricity in Iceland is mostly made from renewable resources and methane is already being burned to reduce emission. One model of the diffusion of AFVs, Driving the Future (DtF) [9] was designed for the United States but can be adjusted to Iceland. The DtF model captures the interaction between the diffusion of AFVs and their corresponding fuel supply infrastructure. The DtF model can be used to explore a possible future for AFVs and total emission reduction. In this thesis we adjust the DtF model to Icelandic conditions and use it to explore potential future of AFVs in Iceland. Different scenarios are implemented in order to explore the effect of different policies on the share of AFVs and on emissions reduction. The research questions are 1) are we doing enough to reduce emission, 2) if not, what can we do better and 3) are many AFV platforms ideal for Iceland or would it be better to choose one platform and focus incentives on that?

In the following chapter we present the background. Chapter 3 is about system dynamics and Chapter 4 describes the main parts of the model Driving the Future. Data and parameterization are described in Chapter 5 and scenarios and results in Chapter 6. Discussions are in Chapter 7 and conclusion in Chapter 8. In Appendix A acronyms used are shown.

Chapter 2

Background

According to Struben [10] people will not consider an alternative fuel vehicle platform until they are familiar enough with it and that people gain familiarity through exposure, word of mouth and marketing. Struben also points out that it is hard for AFVs to grow in the market because they are up against a mature market since they are still more expensive and do not have the same utility as internal combustion engines (ICE). For a successful diffusion of AFVs, governments will have to make an effort to help them establish their part in the market. Struben finds in his studies [10] that the ICE vehicle lifetime does not help the AFVs diffusion. Since ICEs average lifetime is more than a decade it will take a long time for AFVs to gain a reasonably large share of the marked due to a slow turnover. Struben's idea about how familiarity accumulates through word of mouth is supported by Zhang, Gensler and Garcia [11], who used an agent based simulation model to explore the factors that could boost AFV diffusion. They found out that word of mouth could lead to consumers higher willingness to pay which suggest that the value of AFV for consumers increases through word of mouth.

The model Driving the Future was made by Dr. David Keith based on Struben's idea of consumer familiarity, that is, people will not consider purchasing a vehicle from an alternative fuel platform without sufficient knowledge of it. The utility of each platform also affects the consumers choice to purchase a vehicle from a particular platform and the most important utility variables are purchase price, fuel cost, range and the availability of fuel supply infrastructure. The model uses the utilization of the infrastructure to calculate how the number of stations coevolves with the installed base and how the Original Equipment Manufacturers (OEM, the auto makers) revenue affects the vehicle price and fuel efficiency improvements. This model was originally made to explore the adoption of Toyota Prius in the US but has been extended to capture gasoline, diesel, Hybrid and

Plug-In technologies and used to study the role of Hybrids in the transition to plug-in vehicles [9].

The DtF model has been adapted to Indian market by Neerkaje [12], where the dynamics of AFVs diffusion were explored through different scenarios. Part of the adjustment work was to add a structure that captured the total fleet expansion and to extend the model to eight vehicle platforms (gasoline vehicle (GAS), Hybrid Electric Vehicle (HEV), Plug-In Hybrid Electric Vehicle (PHEV), Battery Electric Vehicle (BEV), Compressed Natural Gas (CNG), diesel, hydrogen (H_2) and biofuel (BIO)). The results are focused on the sales and installed base of each vehicle platform and how the number of fuel pumps increases when installed base of a platform increases. Result showed that annual greenhouse gas emissions (GHG) varied between scenarios and that an increase in EVs does not necessarily help reduce GHG, partially because most of the electricity in India comes from coals. The DtF model is constantly evolving and it is described in the next chapter.

Dr. Ehsan Shafiei et al. have been studying the diffusion of AFVs in Iceland using simulation models. Shafiei has integrated agent-based and system dynamics modeling to simulate the AFV diffusion [13]. Shafiei has also adjusted and applied a simulation model on Iceland, called UniSyd_IS [14, 15, 16, 17]. The UniSyd_IS model is based on a model from New Zealand and models the energy sector and explores fuel demand, fuel supply and associated costs. It captures the interaction between electricity, hydrogen, biogas, bioethanol, biodiesel and the vehicle fleet but gasoline and diesel fuels are modeled exogenously. The consumers choice to buy an AFV is modeled as a function of both consumers individual preferences and social influence on consumers. The focus is on the energy supply sector which is thoroughly modeled, both for present capacities and future capacities, to be able to explore the possible future energy supply until the year 2050 and associated costs. The model offers the possibility to enter different policies about how the government could use taxes and incentives to be able to stimulate the diffusion of AFVs and reduce GHG. The model assumes that the total vehicle fleet grows with time and this growth is modeled as a function of population until it reaches a saturation level. A plausible future of the amount of fossil fuel and GHG emissions, and vehicle fleet composition are a part of the results from this model.

Chapter 3

System dynamics simulation

System dynamics was created and developed by Jay W. Forrester in the late nineteen-fifties and early nineteen-sixties. Forrester argued that there was a need for a better method to understand complex systems than those who were available at that time. System dynamics is a method to describe and model non-linear, complex systems to understand the behaviour of a system. This method is often used when variables in a system interact internally and affect each other. When a variable affects another variable and and the latter one affects the first one back it creates a feedback loop. Many variables can be in each feedback loop and the effects on a variable could be with time delay. A system dynamics model usually consists of many feedback loops where the variables interact and the loops can either be reinforcing or balancing. A reinforcing feedback loop is a loop where an increase in one variable eventually leads to more increase in the same variable. A balancing feedback loop is when an increase in one variable eventually leads to a decrease in the same variable. When a variable affects a system but the system does not affect the variable back, the variable can be modelled exogenously and is therefore not a part of a feedback loop. The model boundaries should not be too narrow and it is important that all variables that could affect the system somewhat are modelled.

A system dynamics model is usually built from different types of variables. The variables include stocks, flows, parameters and constants. The stocks are differential or integral equations of the flows and they accumulatie/dissipate over the simulation time. Other variables include parameters that are equations to describe the relationship between other parameters, constants and stocks. Building a model requires a definition of the problem and figuring out what variables affect the system and if the system affects the variables back. After modelling a system in a computer simulation platform it is important to verify and validate the model. To verify a model, the modeller verifies that all equations and connections are correctly coded. That includes making sure that units and numerical applications are consistent. Validation includes making sure that the boundaries are adequate and that the model structure is in accordance to the system in the real world. The validation process includes checking how the model behaves, if the outcome is plausible and how sensitive the model is to changes in parameters [18]. In some cases it is possible to use historical data to validate a model. Then a part of the data is used to make the model, determine the equations and values behind the variables so the model behaves like the data. Then the other part of the data is used to compare to the results from a simulation run and see how well the real data fits to the model output. If historical data is not available there are several ways to validate a model but all of them are in the end based on the modellers knowledge on the system. The makes the task of validating a model a diffucult one, but it is an important one. If a model is to be used to analyze the system and help with policy making one needs to be confident that the model corrispondes to the real world.

Many system dynamics simulation software is available and among others are Vensim [19], Stella [20], Forio [21] and Simulink which is intergrated to Matlab [22].

The DtF model is built with system dynamics approach and the Vensim software is used.

Chapter 4

Driving the future - the model

The DtF model consists of feedback loops that interact with each other. The model offers can be used to explore the share of each platform given different policies along with emissions and fuel consumption for light duty vehicles. The focus is on the accumulation of familiarity, utility of each vehicle platform and on the coevolution of alternative fuel vehicles and their refueling infrastructure. Utility of a platform is assumed to have an affect on the consumers' choice to purchase an AFV. The utility is modeled as weighted average of factors that are often used in models for diffusion of AFVs. In the DtF model it is assumed that familiarity accumulates with word-of-mouth, marketing and exposure but dissipates over time if word-of-mouth, marketing and exposure are not present because people forget what they have seen and heard. When consumers discard their vehicle it creates a demand for a new vehicle, and the familiarity and utility of each platform determines the share of consumers who purchase vehicles from each platform. In the DtF model it is assumed that when the installed base of a platform grows there is more exposure and word of mouth and also more marketing, since it is assumed that the OEMs use a part of their revenue in marketing, which in turn increases familiarity. Part of OEMs revenue is used for Research and Development (R&D) on fuel efficiency which leads to less refueling cost and therefore better utility reinforcing the affinity towards that platform. With larger installed base the vehicle purchase price reduces due to learning by doing and scale of economies, increasing the utility of the platform. Larger installed base also leads to better utilization of the fuel supply stations, creating more revenue for each station and a demand for more stations. When there are more available stations, the fuel search cost decreases, leading to better utility of the vehicles. Figure 1 shows the main elements of the model.

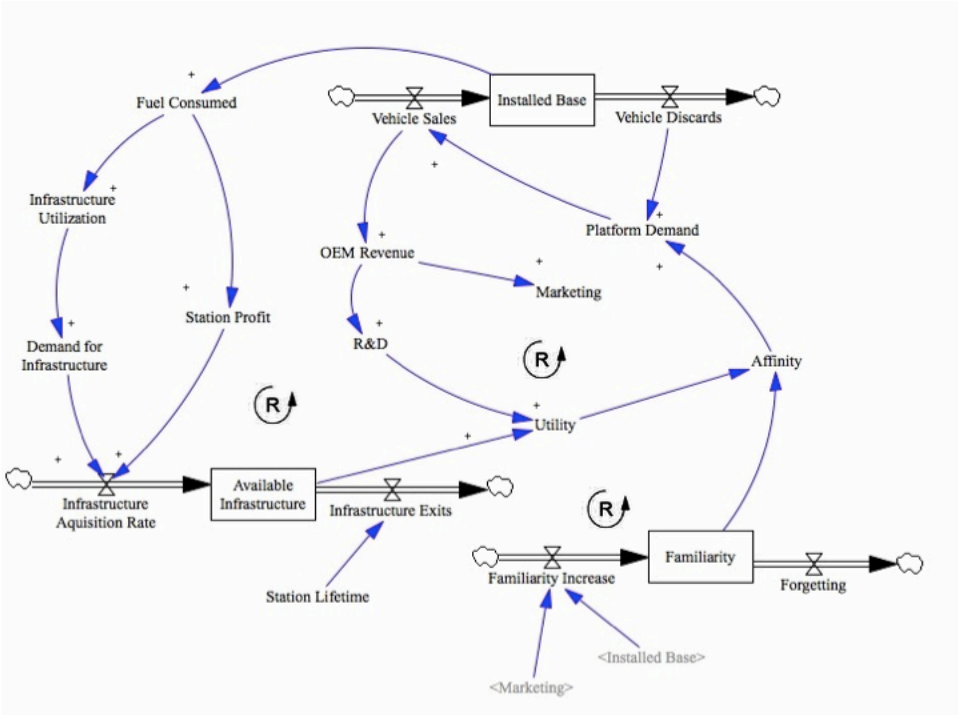

Figure 1: Main elements in the DtF model

The DtF model makes some simplifications and assumptions. For example, on top of the vehicle price is the price of a home charger (for plug-in vehicles), that is, it is assumed that consumers that purchase a plug-in vehicle buy a home charger as well. The model makes the assumption that there are no constraints on production or distribution of vehicles, if there is a demand for vehicles there is a sale. The familiarity of GAS platform is 100%, assuming that all consumers have full familiarity of that platform. The fuel supply is not constrained, if there is demand for fuel it is available. In order to boost an adoption of a platform the model offers the chance to add incentives to consumers, infrastructure and manufacturers. All units are in $ and miles and the simulation time is from 2000-2050.

In the following sections, the main elements of the model are described. For a more detailed description of the DtF model, see [9] and [12].

4.1 Platform utility

Consumers affinity towards a platform is affected by utility and familiarity accumulation, as shown in Figure 2.

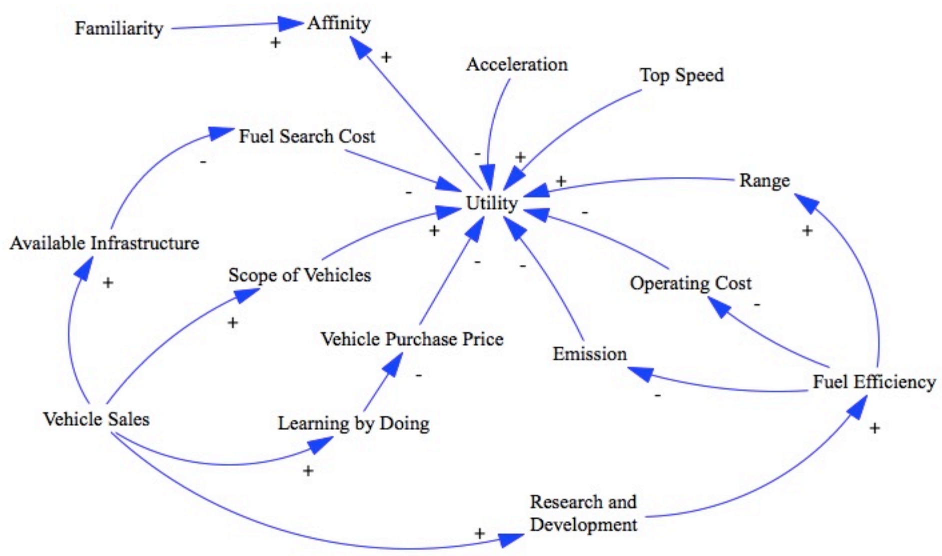

Figure 2: Utility of Platforms

The utility is modeled as the sum of commonly used variables that are assumed to affect consumers vehicle purchasing decision. Those variables are purchasing price & household income, operating cost, acceleration, top speed, range, emission, fuel search cost and the scope of vehicles in the platforms.

U_1 is the purchase price factor and β_1 the purchase price weight. U_1 is calculated from the effective vehicle price and household income multiplied with the purchase price weight, U_3, as shown in equation 1.

$$U_1 = \frac{VP_j/1000}{Ln(HI)} \cdot \beta_1 \tag{1}$$

VP_j is a vector of vehicle price of each platform and HI is median household income. Household income is used since the economic status of the country, along with vehicle price, affects consumers to purchase a vehicle.

U_2 is the vehicle operation cost factor and is shown in equation 2.

$$U_2 = (\frac{FP_r}{FE_j} + VmtTax_j) \cdot \beta_2 \tag{2}$$

$\mathrm{FP_r}$ is the retail fuel price of each fuel r, $\mathrm{FE_j}$ is the fuel efficiency and $\mathrm{VmtTax_j}$ is vehicle miles travelled tax.

$\mathrm{U_3}$ is the vehicle acceleration factor and is the time in seconds it takes a vehicle to go from 0-30 mi./h times a weighing factor β_3. $\mathrm{U_4}$ is the vehicle top speed multiplied with a weighing factor, β_4.

$\mathrm{U_5}$ is vehicle range factor and is the vehicle range ($\mathrm{VR_j}$) multiplied with range weight as shown in equation 3. The vehicle range improves when fuel efficiency improves as shown in equation 4.

$$U_5 = VR_j \cdot \beta_5 \tag{3}$$

$$VR_j = FE_j \cdot TC_j \tag{4}$$

$\mathrm{TC_j}$ is tank/battery capacity of vehicles of platform j.

$\mathrm{U_6}$ is an emission factor and is calculated as the fraction of emission per mile times the weighing factor as shown in equation 5. The emission fraction is the emission per mile from each platform divided by emission from gasoline vehicles per mile as shown in equation 6.

$$U_6 = EF_j \cdot \beta_6 \tag{5}$$

$$EF_j = \frac{EmissionPerMile}{EmissionPerMile[Gas]} \tag{6}$$

$\mathrm{U_7}$ is fuel search cost factor and is fuel search cost ($\mathrm{FSC_j}$) multiplied with search cost weight, β_7, as shown in equation 7. The fuel search cost is affected by full refueling cost $\mathrm{FRC_j}$ and vehicle miles travelled per year as shown in equation 8.

$$U_7 = FSC_j \cdot \beta_7 \tag{7}$$

$$FSC = \frac{FRC_j}{VmtPerYear} \tag{8}$$

The full refueling cost affected by all cost associated with refueling a vehicle as shown in equation 9.

$$FRC_j = (SC_j + WC_j + SeC_j + Oof_j) \cdot NoRefuelsPerYear \quad (9)$$

$SC_j$is search cost, WC_j wait cost, SeC_j is refueling cost and Oof is the cost of running out of fuel. NoRefuelsPerYear is number of refuels/recharges per year. All of the cost variables are affected by the value of time which is assumed to be $40 per hour. The search cost is the cost of finding a refueling station and is affected by the number of stations since the average distance between stations is number of stations divided by the area of the country. The wait cost is also affected by the number of stations. Fewer stations lead to more utilization which could lead to a wait for a pump/plug. Service cost is the cost of time while refueling a vehicle. Out of fuel cost is the probability of running out of fuel times a out of fuel recovery time which is assumed to be 5 hours.

U_8 is a scope factor, sometimes called make and model factor. It covers the chance that a consumer finds a vehicle of his/her requirements. The scope factor is multiplied with the scope weight as shown in equation 10.

$$U_8 = Scope \cdot \beta_8 \quad (10)$$

The scope is cumulative sale of vehicles from each platform divided by a reference value. It is assumed that gasoline platform already has enough models of vehicles to fulfill all consumers requirements and therefore this factor does not have negative effect on gasoline platform.

The betas are weighing factors for each utility and their names and values are shown in Table 1.

Table 1: Utility Weighing Values

Variable	**Variable Name**	**Value**
β_1	Purchase Price Weight	-0.361
β_2	Operating Cost Weight	-0.17
β_3	Acceleration Weight	-0.149
β_4	Top Speed Weight	0.272
β_5	Range Weight	0.2
β_6	Emission Weight	-0.673
β_7	Search Cost Weight	-0.17
β_8	Scope Weight	0.5

All weighing values used are same as Keith used in his dissertation [9] except emission weight which comes from Brownston et al. [23].

The vehicle purchase price reduces with learning-by-doing and scale of economies. A normal economic growth in household income is assumed. With higher income and lower vehicle price the utility increases.

Fuel efficiency improvements and fuel price reduction lead to an increase in the utility function. Acceleration and top speed are constant during the simulation but the range and emissions improve with better fuel efficiency. Fuel search cost is affected by the value of time it takes to find a refueling station, wait for a fuel pump, the time it takes to refuel the vehicle and out of fuel recovery time, times the chance of running out of fuel. The scope improves with vehicle sales because more sales in a platform leads to more diversity of vehicles. When the utility function increases the affinity towards a platform increases and creates more demand for each platform.

4.2 Platform familiarity

Initial familiarity for each platform comes from marketing but if there is no marketing present, no familiarity will accumulate and therefore consumers will not adopt vehicles from that platform. Therefore additional market spending is modeled exogenously to boost initial familiarity and these spendings continue throughout the simulation. The additional market spending is on top of regular spending which is affected by the OEM revenue as equation 11 displays.

$$MS = RmS + AMS \tag{11}$$

MS is total market spending, RmS is regular market spending and AMS is the additional market spending.

The model uses nested multinomial logit function for the consumer choice. It is assumed that people first choose if they want a liquid fuel vehicle, plug in technology, H_2, biofuel, HEV, CNG. If liquid fuel is chosen, people then choose between gasoline and diesel, and if plug-in technology is chosen, people choose between plug-in hybrid and battery electric vehicles. It is assumed that if people are familiar enough with the plug-in technology, people will consider either PHEV or BEV option for purchase. Formulation for the nested multinomial logit function can be seen in [12].

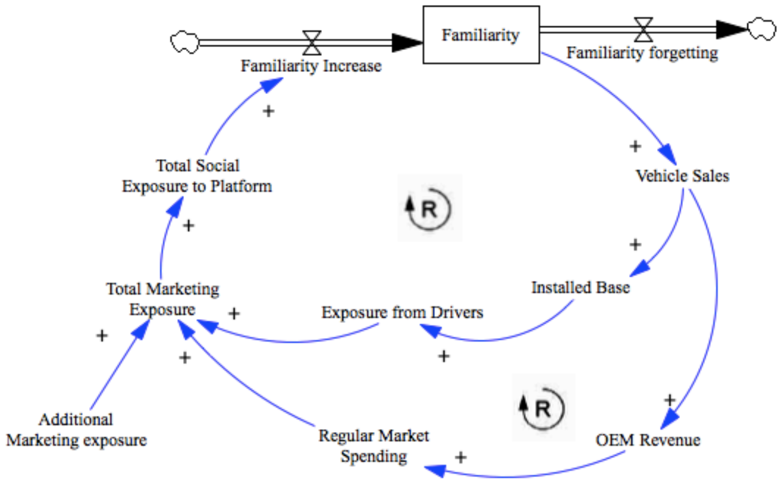

Figure 3: Familiarity acumulation

When familiarity of a vehicle platform increases there is more vehicle sale, as shown in Figure 3. Vehicle sales affect the total installed base which leads to more exposure from drivers. Drivers of a platform transfer knowledge of that platform over to non-drivers, increasing familiarity. Vehicle sales also affect the OEM revenue. When the OEM revenue increases, more is spent on marketing, increasing familiarity further. The gain in familiarity depend on the effictiveness of marketing and on the effective contact rate to drivers. The values for these variables are used are not changed from the US values.

To find the total market spending over the simulation time, a stock variable was added. Flow into the stock variable is market spending which cumulates over the simulation time. All values connected to familiarity are the same as in Keith's dissertation [9] except the exogenously added market spending which is used to establish initial familiarity in scenarios.

4.3 Infrastructure

The available infrastructure is affected by the station profitability and utility of refueling pumps, see Figure 4. The stations profit depends on ancillary revenue, operating profits and fixed costs. Ancillary revenue are sales of vehicle related product, candy, soda and other services. The operating profit is the difference between the pump revenue and cost as shown in equation 12. The pump costs and revenue are dependent on how much fuel is consumed, operating costs, feedstock cost and the stations markup as shown in equations 13, 14 15. Fuel consumed by the installed base are dependent on vehicle miles travelled and with a larger installed base, the profits increase, leading to more stations.

$$Profit = Revenue + Cost \tag{12}$$

$$Revenue = FC_r \cdot FP_r \tag{13}$$

$$Cost = FC_r \cdot (FeedstockCost_r + OC_r) \tag{14}$$

$$FeedstockCost = \frac{FP_r}{1 + Markup} \tag{15}$$

$\mathrm{FC_r}$ is fuel consumed, $\mathrm{FP_r}$ is retail fuel price and $\mathrm{OC_r}$ is pump operating cost. The stations pump utility is affected by the installed base, refueling time and number of refuels per year, with bigger installed base creates more utility of fuel pumps which leads to more stations. To help increase the number of stations and overcome the chicken and egg problem, stations can be added exogenously as an incentive to the infrastrcture from the government, meaning that the cost of these stations does not affect the profit og the stations.

The model assumes that consumers have buffer which is the miles left in the tank/battery when the consumer chooses to look for a refueling station. The buffer decreases the vehicles effective range and is in the model because consumers do not empty their tank completely before looking for a refueling station. This buffer depends on the density of stations, if the distance between stations is long, consumers choose a bigger buffer, while many available stations reduces the distance between them causing a smaller buffer.

The fuel consumed by PHEV drivers is gasoline, electricity from public charging and from home charging but only the former two have affect on the infrastructure profits. It

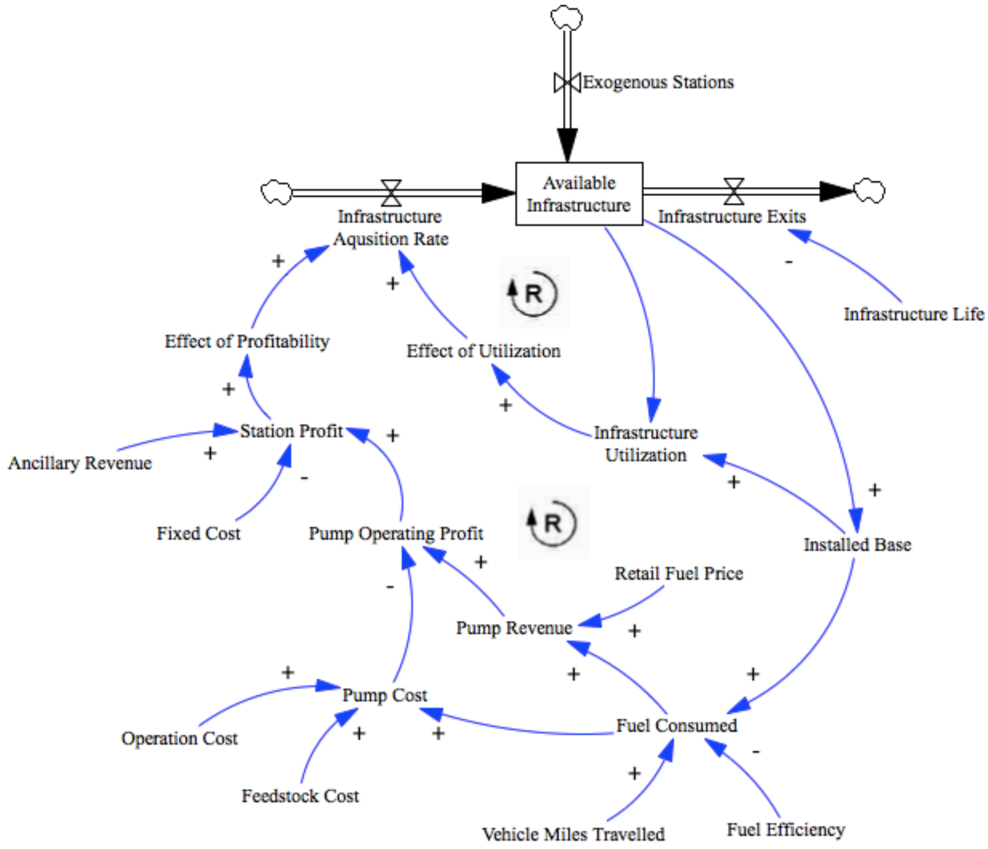

Figure 4: Effect on Available Infrastructure

is assumed that a part of the electric miles come from home charging and if that charge is not enough for average daily trips, the consumers will have the choice of finding a plug station and charging the vehicle or switching to gasoline. The choice of finding a charging station is formulated with a logit choice function that has utility factors such as search cost, wait cost, electricity price and emissions from gasoline.

4.4 Energy Prices

Energy prices have an effect on the fuel providers revenue and on vehicle operating cost. Data for energy prices for the years 2000-2011 are used but after 2011 energy prices either rise/fall depending on the fuel. Gasoline, diesel and CNG prices are assumed to change at a constant rate, chosen by the user of the model, till 2050. Biofuel price is expected to decrease based on experience from production of biofuel and from worldwide ethanol production experience. Same goes for H_2 fuel price, it reduces with both domestic and worldwide experience. For electricity price, it is assumed that a part of the electricity used is conventional electricity and a part of renewable electricity. The fuel price is shown in Figure 5. The renewable electricity is assume to have higher price than the conventional electricity price. After 2011 the electricity price changes at a constant rate. A logit choice function is used to determine the parts of conventional and green electricity and a weighted average of the prices are used as the retail electricity price.

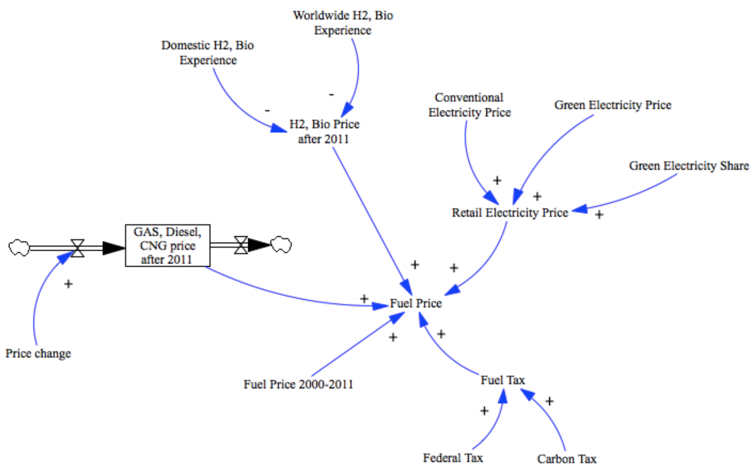

Figure 5: Fuel Price Formulation

The taxes on fuel price are calculated seperately and consist of state taxes, federal taxes and carbon taxes. The state taxes are a constant through the simulation but the federal taxes and the carbon tax can be used to explore the effect of increased taxes on the share of vehicle installed base. The carbon tax is found with carbon price and greenhouse gas factors for all fuel types. Both the federal and carbon tax grow linearly from a chosen start year to a chosen end year. The model was formulated to remove the federal taxes from the fuel price and then add a fuel tax that can be raised through the simulation to explore the effects of rising taxes on the share of each platform.

The taxes on fuel price in Iceland are not divided into state and federal taxes like in the US. In Iceland one tax price is added on gasoline price and another one on top of diesel price which means that if there is difference in fuel price between stations it is only due to difference in station markup. A value added tax (VAT, %) was added to the model. The model starts by removing the VAT % from the fuel price and then the federal tax is removed. The fuel tax added includes the federal tax and carbon tax. VAT is added again and can be chosen by user to explore the effect of raised VAT tax.

99% of electricity produced in Iceland comes from a renewable energy sources [24]. The share of electricity from renewable energy sources and electricity price does not seem to be related in Iceland. Therefore the connection in the model which calculates the price according to the share of renewables is cut and only one electricity price is used.

4.5 Greenhouse Gas Emissions

The fact is that in the US the electricity used is largely from non-renewable energy sources [25]. The GHG factor for electricity is calculated as a weighted average of the GHG factor for renewable energy and the GHG of non-renewable energy. The model offers the user to change the share of renewable energy which is appropriate since the US is trying to establish a better energy security which includes increasing renewable energy share [26]. This does not apply to Iceland because of the high percentage of renewable energy. Therefore the link between the share of renewable energy and the GHG factor is cut and assumed that renewable energy is 100%.

Greenhouse gas emissions factors for all fuel types are used, with VMT, to find the total emissions by all platforms. The emissions for manufacturing vehicles and batteries and emissions when recycling and disposing a vehicle are added to find the total annual and cumulative emissions over the simulation. The emission factors apply to Iceland as well as to the US and are therefore not changed.

4.6 Vehicles

The initial installed base is assumed to contain only vehicles from gasoline and diesel platforms. The vehicles are divided into age groups, 0-4 years old, 5-8 years, 9-12 years and 13+ years old. It is assumed that each group has a retirement fraction that decreases the number of vehicles in each group. The retirement fraction is due to vehicle brake-down or destruction (e.g. after an accident). The retirement fraction is different between groups since the chance of a vehicle being retired increases with age. A part of each group jumps to the next group during simulation time, according to an ageing fraction. These jumps between groups are a part of an ageing process, for example a part of the vehicles from the 0-4 year group fall into the 5-8 year group. The vehicle ageing process is shown in Figure 6. When there is demand for (new) vehicles those vehicles go straight to the 0-4 group. Vehicles from the 13+ group don't have an ageing fraction, only the retirement fraction. Discards from all age groups control the total platform demand at each time and the affinity towards the platforms controls the share of vehicles from each platform.

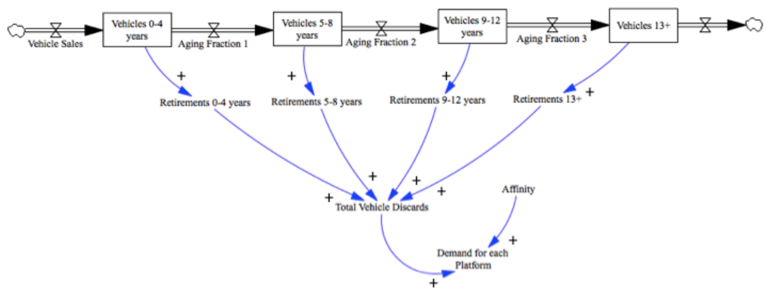

Figure 6: Vehicle Ageing Process

The effective vehicle price is the manufacturers suggested retail price (MSRP) with manufacturers markup. It is assumed that BEV and PHEV consumers purchase a home charger and that adds on top of the vehicle purchase price. If vehicle incentives to consumers are available that amount is subtracted from the effective price. The MSRP is calculated as the vehicle manufacturing cost plus the manufacturers markup. The manufacturers revenue affects marketing, which increases familiarity, and R&D which increases fuel efficiency and decreases the manufacturers production cost. The vehicle incentives are modeled exogenously and are considered as incentives from the government.

The DtF model assumes that the MSRP is directly related to the effective vehicle price but the MSRP does not represent the vehicle price in Iceland like it does in the US. This is partially due to distribution and taxation. The link between MSRP and effective vehicle price are cut and a variable for initial vehicle price is added. A reduction rate of vehicel price is added to cover the reduction in vehicle price due to learning-by-doing and scale of economies. Learning-by-doing is an economical concept that states that e.g. factories learn from production experience and can with a learning process increase output without increasing cost by significant amount. Scale of economies is when the output of a factory increases, the companies fixed cost spreads over more produced items and therefore each item is cheaper to produce. Both lead to reduced cost of production which should result in lower price. The relationship between vehicle price and reduction rate is shown in Equation 16. Model code for modifications made are shown in Appendix B.

$$VehiclePrice_t = VehiclePrice_0 \cdot (1 - ReductionRate)^{(t-t_0)} \qquad (16)$$

Chapter 5

Data and parameterization

The DtF model is dependent on large amount of data. Part of the data in the model is real data but part of the values used are assumptions. To adjust the DtF model to Iceland it is necessary to change some of values in the model but some values apply just as well to Iceland as to the US. The data used to adjust the DtF model to Iceland are described below. Part of values used are obtained in ISK and all are converted to dollars. The rate of exchange is 130 ISK/$ from [27], 20. Jan. 2016.

5.1 Vehicle Data and assumptions

The DtF model assumes that the total vehicle fleet stays constant through simulation. In Iceland the vehicle fleet has grown since 2000 and it is assumed that the fleet will continue to grow [28]. The assumption that the total fleet size stays constant does therefore not fit well to Icelandic situation. The year 2015 was chosen as a representative year for the total vehicle fleet size. It is assumed that in the year 2000 two platforms are introduced to the market, gasoline and diesel. The gasoline and diesel platforms have an initial installed base of 166 thousand gasoline vehicles and 60 thousand diesel vehicles [29]. HEV platform is introduced in 2007 and PHEV, BEV and CNG (methane) platforms are introduced in the year 2015 and H_2 in 2020. The initial installed base for AFVs is zero. Regular spending on a platform is a fraction of vehicle revenues. For HEV platform an additional spending on marketing is $30M from 2007-2009, to boost initial familiarity.

The vehicle attributes affect the consumers decision to purchase a vehicle. Vehicle attributes for 2016 model of representative vehicles of each platform is used. The representative vehicles, for those platforms already in Iceland, are chosen based on a popular model, Toyota Avensis for GAS and diesel platforms, Toyota Prius for HEV and PHEV platforms. For BEV platform Kia Soul is used, for CNG Hyundai Grand i10 and Volkswagen Golf is chosen (not all attributes available for either one) and for H_2 the attributes of Honda FCV is used. The representative vehicles can be seen in Table 2.

Table 2: Representative Vehicles for platforms

Platform	Representative Vehicles
GAS	Toyota Avensis
HEV	Toyota Prius
PHEV	Toyota Prius Plug-in
BEV	Kia Soul
CNG	Hyundai Grand i10 & Volkswagen Golf [a]
Diesel	Toyota Avensis
H_2	Honda FCV

[a] Not all attributes found for either vehicle

The assumption that 2016 models can be used as a representative model year is based on the fact that the relative comparison is most important. It is better that data for all representative vehicles come from the same model year. The vehicle attributes that affect the utility can be seen in Table 3. The tank size, top speed and acceleation are constants through the simulation

The DtF model assumes that fuel efficiency improves with R&D. R&D is affected by the OEM revenue but the total sale of vehicles in Iceland is very little, for example compared to the US.

Therefore the fuel efficiency through the simulation time is close to a constant. The values for fuel efficiency for the 2016 models are assumed to be an average value for the time frame.

The vehicle lifetime is assumed to be 12 years, value of time 40$/h. [14] and the average speed 40 mi./h [9]. The average speed and value of time is used to calculate the cost of looking for a fuel station. The number of fuel stations is divided by the total area of the country to get the average distance between stations. Iceland is almost 40.000 mi.^2 but around 75% of it is considered highland [41]. Icelands effective area is used in the simulation, or 10.000 mi.^2. Median household income is used with the vehicle effective price to find the purchase price utility and the initial value is 31.500 $/year [42] with a 2% income growth.

Table 3: Vehicle Attributes

Platform	Tank	Acceleration[a] [sek]	Top Speed [miles/h]	Initial Fuel Efficiency	Source
GAS	16 gal.	3.6	125	39 mpg	[12, 30]
HEV	11.4 gal.	4	113	79 mpg	[12, 31]
PHEV	11.9 gal. + 4.4 kWh	4	113	95 mpg [b]	[12, 32, 33, 34]
BEV	27 kWh	3	90	0.2 kWh/mi.	[12, 35, 36]
CNG	11.4 gal.	4.5	121	44.7 mi./gal.	[12, 37, 38]
Diesel	16 gal.	4.5	115	56 mpg	[12, 30]
H_2	5 kg	3.5	125	93 miles/kg	[12, 39, 40]

[a] Acceleration is the time it takes the vehicle to fo from 0-30 mph.
[b] Combined gasoline and electrical Fuel Efficiency.

Initial vehicle price is assumed to be from the 2016 models of vehicles and are listed in Table 4 with the reduction rate and end price. Direct comparison of the vehicles is hard since these vehicles are of different body styles and have different power.

Table 4: Vehicle Prices and reduction rate

Platform	Initial Price [$]	Reduction Rate [%]	End Price [$]	Source
GAS	30.000	0	30.000	[30]
HEV	35.000	0.2	32.110	[31]
PHEV	41.000	0.6	32.230	[32]
BEV	36.000	0.25	32.570	[35]
CNG	31.000[a]	0	31.000	[43]
Diesel	33.000	0	33.000	[30]
H_2	72.300	1.5	42.600	[44][b]

[a] CNG Price is assumed to be 1000$ more than GAS.
[b] H_2 vehicle price with value added tax

The GAS, diesel and CNG vehicles all have internal combustion engine. The internal combustion engine vehicles are so widespread that scale of economies and learning-by-doing will likely not affect the vehicle prices to any extent. Even if scale of economies and learning-by-doing would have any effect, OEMs are always improving the technology in vehicles which keeps the price up. Therefore the GAS, diesel and CNG vehicle price stays constant through the simulation. The H_2 prices are on the other hand assumed to reduce due to those factors and a reduction rate of 2% is chosen which gives the final price of about $43.000 by the end of the simulation. HEV, PHEV and BEV vehicle prices are also assumed to decrease but at a slower rate. HEV vehicle price is assumed to reduce until close to GAS vehicle price and PHEV ad BEV vehicle prices close to diesel vehicle price. The reduction rates are found by trial and error until the end price of the HEV platform is close to Gas platform price, and PHEV and BEV platforms are close to the diesel vehicle price. The DtF model assumes that consumers who purchase a vehicle from PHEV and BEV platforms also purchase a home charger. EV home charger is assumed to cost $2000 [45].

Even though the formulation for the effective vehicle price has been changed, the OEMs costs and revenue still affects marketing and therefore the familiarity of a platform. The OEMs marketing efforts are left in the model and assumed to come from the vehicle dealers since it is assumed that they will spend more money on marketing for a platform that returns revenue to them.

The real fuel prices for gasoline [46], diesel and methane [47] for the years 2000-2011 are used. The gasoline and diesel prices increased during that time due to the economic recession in 2008. Therefore the gasoline and diesel prices are reduced to around 5.5$/gallon and 4.9$/gallon in the year 2016, respectively, but after that the prices are assumed to grow total of 10% by the end of 2050. The methane price is also assumed to raise by 10% during the simulation. The electricity price in the year 2000 was 5.6 cents/kWh [48] and was raised linearly to 12.3$/kWh [49] in the year 2011 and raised by 10% total until 2050 (note: home electric prices, also used for public charging). The hydrogen price is assumed to be 20% higher than per GGE diesel [50] and after 2011 the hydrogen price reduces based on worldwide H_2 production and learning by doing. The fuel prices are shown in Figure 7. Note. the fuel prices are in $/GGE. GGE is abbreviation for Gasoline Gallon Equivalent and is a measurement for the amount of alternative fuel which containes the same energy content as one gallon of gasoline. This measurement is used in the DtF model for comparison of fuels.

Taxes on gasoline and diesel are in total 210 cents/gallon and 184.6 cents/gallon, respectively, but methane, electricity and H_2 are excluded from these taxation [51], [52]. Included in these prices is current carbon tax, 17.2 $/tonnes CO_2 (based on current carbon price of gasoline in Iceland 2016) [53]. The greenhouse gas emissions from electricity, H_2 and methane are considered to be zero and therefore, if carbon tax is increased, they will not raise the prices for those fuels.

Vehicle miles travelled (VMT) for gasoline vehicles are 7.500 miles/year. The model assumes that VMT changes with different range and operating costs but in Iceland VMT for gasoline has stayed close to a constant for many years. Therefore it is assumed that

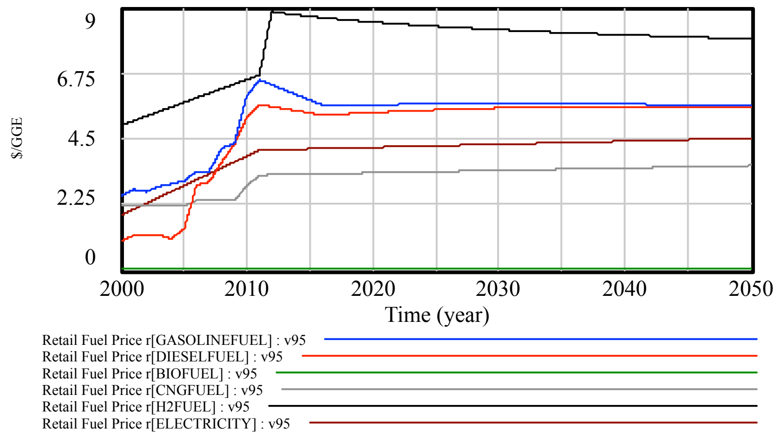

Figure 7: Retail Fuel Prices

operating costs and range does not have much affect on VMT and the model is calibrated so that VMT for gasoline stays close to a constant of 7.500 miles/year. For diesel it stays close to a constant value of 10.000 miles/year [29]. For other platforms there is no reason to assume less mileage/year except for BEV platform because the range is considerably less than for gasoline platform and a value of 5.000 miles/year is chosen. For other platforms, the model is calibrated so that VMT is close to a constant value of 7.500 miles.

5.2 Infrastructure

The station profit affects the available infrastructure and is calculated from pump operating profits, ancillary revenue and fixed cost. The ancillary revenue for fuel stations can be obtained [54] but in Iceland all stations have both gasoline and diesel fuels. That means that the ancillary revenues for gasoline and diesel are combined and it is diffucult to divide them onto each fuel. Therefore the ancillary revenue are set to zero. The fixed cost is more difficult to find and since the ancillary revenues are set to zero, adding fixed cost would result in wrongly reduced revenue. The fixed cost is set to zero noting that this means that the model calculates the available infrastructure solely on the revenue from fuel sales and ignoring the cost of constructing a new infrastructure. The station markup is assumed to be 13% [55].

In fuel stations in Iceland there is always one diesel pump for every gasoline pump. Therefore the number of pumps per station for gasoline and diesel are the same as well as the number of stations. The initial available stations are 287 gasoline and diesel stations [56, 57, 58, 59, 60, 61]. Initial number of stations for all other platforms it is zero. The number of pumps per station are assumed to be (on average) three gasoline and diesel pumps, based on research on fuel station webpages. Number of pumps per station for AFVs is two methane pumps, one plug in charge and one H_2.

The target utilization for the pumps was found with trial and error. In Iceland there are many gasoline/diesel stations compared to the number of vehicles. A value for utility was chosen such that the number of gas stations would not quickly decrease after simulation start which resulted in 6.5% target utilization value. It is assumed that PHEV drivers do not use the public charging infrastructure. Therefore PHEV platform has no affect on the utility of the charging infrastructure or the charging station profit. This is because the chance that a PHEV driver takes the time to charge in a public station, during daily tasks, is considered very low since it is easier for the driver simply to switch to gasoline.

Chapter 6

Scenario analysis and results

Different scenarios are used to analyze different possible future events. In the DtF model additional marketing, fuel stations and subsidies are added exogenously to boost different AFV platforms. The additional marketing is on top of the marketing efforts that are affected by the vehicle sale. The BEV, CNG and H_2 platform scenarios are analyzed and compared to a base case. The base case is set up to resemble the current situation in the vehicle fleet and a plausible future. One scenario contains all incentives for all AFV to analyze the competition between all AFV platforms. The incentives for all scenarios are shown in Table 5. The incentives are the amount spent on additional marketing and number of stations that are exogenously added.

Table 5: Additional Marketing Cost and Refueling Stations added for all Scenarios

		HEV	**PHEV**	**BEV**	**CNG**	**H_2**
Base Case	Marketing	$100M	$50M	$30M	$100M	0
	Stations	0	0	2 [a]	1 [a]	0
EV Case	Marketing	$100M	$50M	$50M	$100M	0
	Stations	0	0	15 [a]	1 [a]	0
CNG Case	Marketing	$100M	$50M	$30M	$150M	0
	Stations	0	0	2 [a]	5 [a]	0
H_2 **Case**	Marketing	$100M	$50M	$30M	$100	$150M[b]
	Stations	0	0	2 [a]	1	5 [a]
All AFV Case	Marketing	$100M	$50M	$50M	$150M	$150
	Stations	0	0	15 [a]	5 [a]	5 [a]

[b] And a $15.000 incentive for H_2 vehicle purchase.

[a] Stations per year for five years.

6.1 Base case

A base case that captures the current situation in Iceland is set up for comparison to other cases. It reprecents a plausible future if no policies are changed. To establish the base case the additional marketing and exogenous stations are used. An additional market spending for HEV, PHEV, BEV and CNG platforms are used to jumpstart initial familiarity. Exogenous stations are added for BEV and CNG platform to reach current situation. The additional market spending are \$100M for HEV and CNG platforms, \$30M for BEV platform and \$50M for PHEV platform as of 2010. Two charging stations are added each year for five years and one CNG station per year, from 2010-2014. Incentives are shown in Table 6. These numbers are unrealistic for Iceland because they are very high but these numbers should not be taken literal since the additional marketing variable is a control variable. The additional marketing for HEV alone is \$100M but in 2005 the total marketing cost for all platforms available was around \$3.8M [62]. The high cost of marketing could imply that the model does not describe Icelandic conditions well enough in its current state. The additional market spending continue throughout the simulation.

Table 6: Additional Marketing Cost and Refueling Stations added for Base Case

		HEV	PHEV	BEV	CNG
Base Case	Marketing	\$100M	\$50M	\$30M	\$100M
	Stations	0	0	2 [a]	1 [a]

[a] Stations per year for five years.

Figure 8 shows the total installed base for the business as usual case and according to it the gasoline vehicles reduce radically after 2010 while HEV, PHEV, BEV og CNG installed base increase gradually. The diesel platform grows after 2010 but starts to decrease after 2030. The H_2 platform has no share due to no additional marketing to jumpstart initial familiarity. The model results do not reprecent real data for 2015 well because the model finds the share of the platforms from the utility function and the diesel utility is better than for gasoline. The DtF model also assumes that there is no expansion of the total fleet so in order to increase the diesel share, the gasoline share reduces.

In Iceland there has been a trend for the diesel platform. In the past there was a diesel vehicle tax which had the effect that the diesel platform did not pay off for people unless their VMT per year was more than for the average consumer. Even though this diesel tax has been revoked, many consumers feel like the diesel platform does not apply to them because their VMT is around the average and choose the GAS platform. The model does not account for this trend and that explaines the difference, at least partially, in real data versus 2015 model results. After 2010 the HEV, PHEV, BEV and CNG vehicles gradually

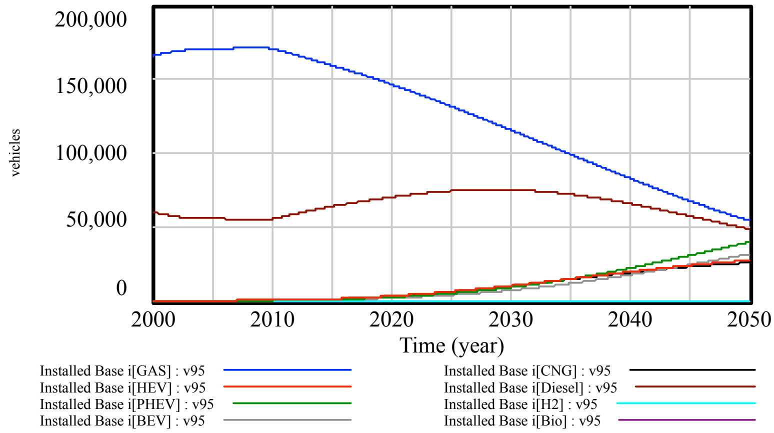

Figure 8: Base Case - Total number of vehicles

increase their share, at first at the expence of the GAS platform but then at the expence of diesel platform as well.

The number of available pumps increases with a larger platform share as can be seen in Figure 9. The number of pumps for gasoline and diesel start out the same but the diesel stations decrease quickly after simulation start. The target utility for the pumps are the same for all infrastructure and there are fewer diesel vehicles than gasoline. Therefore the model reduces the number of pumps for diesel platform. The number of charging stations reaches the number of gasoline pumps by the end of the simulation.

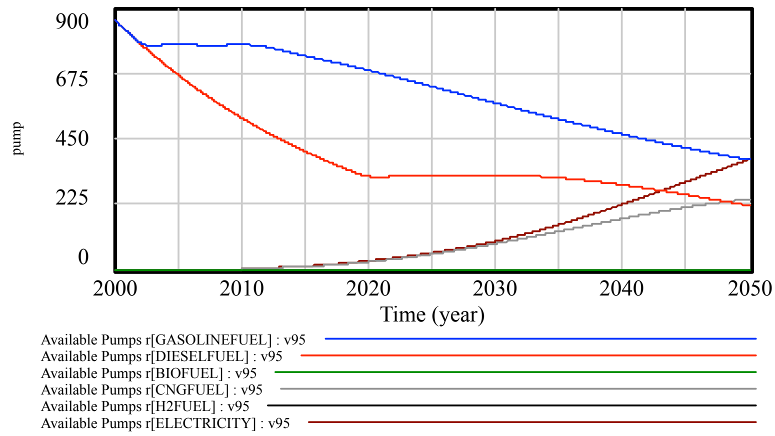

Figure 9: Base Case - Available Pumps/Charging stations for Vehicle Platforms

In Iceland the number of diesel pumps are the same as gasoline pumps so it seems that the utility of diesel pumps is considerably less that for gasoline pumps. The DtF model is formulated for light duty vehicles but lacks formulation for heavy duty vehicles. The heavy duty vehicles mostly rely on diesel and therefore the model does not capture the real dynamics of the infrastructure.

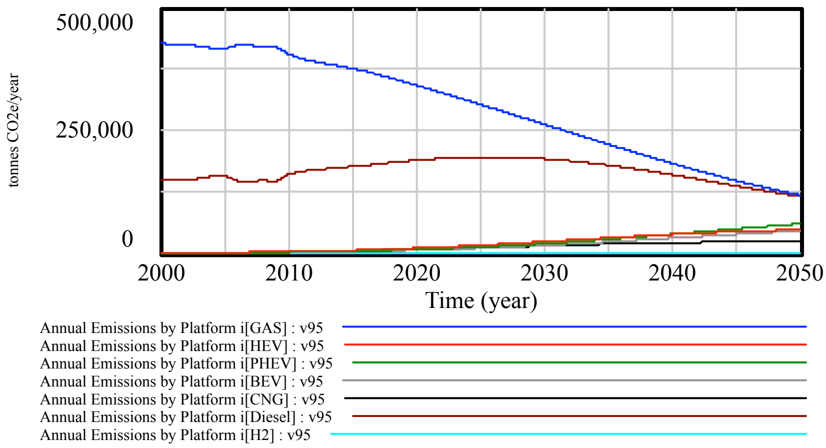

Figure 10: Base Case - Annual Emissions from Vehicle Platforms

The model finds the total emission from all platforms and the results from the base case can be seen in Figure 10. The emission for gasoline and diesel platforms reduces due to a decrease in the total share of gasoline and diesel vehicles. Even though the emissions from BEV and CNG are considered zero there is always emission from production and discarding of the vehicles. The base case shows total emission of 26M tonne CO_2 over the simulation time and a total of around 30% reduction of emissions from 2000-2050.

6.2 EV Case

In the EV scenario incentives to boost BEV platform are added. Additional market spending for BEV platform is set to $50M and exogenous charging stations are 15 per year for five years as can be seen in Table 7

Table 7: Additional Marketing Cost and Refueling Stations added for EV Case

		HEV	PHEV	BEV	CNG
EV Case	Marketing	$100M	$50M	$50M	$100M
	Stations	0	0	15 [a]	1 [a]

[a] Stations per year for five years.

The PHEV platform does not use the public charging infrastructure. Therefore the PHEV platform does not benefit from the charging stations added.

As Figure 11 shows, the share of BEV vehicles rises above all other AFVs. The BEV total installed base surpasses the diesel installed base, leaving only GAS with a larger share. The BEV platform reaches a share of around 46.000 vehicles. All other platform shares decrease from the Base case scenario.

The number of charging stations increases beyond the exogenously added stations, as can be seen in Figure 12. The number of charging stations is higher than the number of gasoline pumps even though the share of BEV platform is similar to the share of GAS platform.

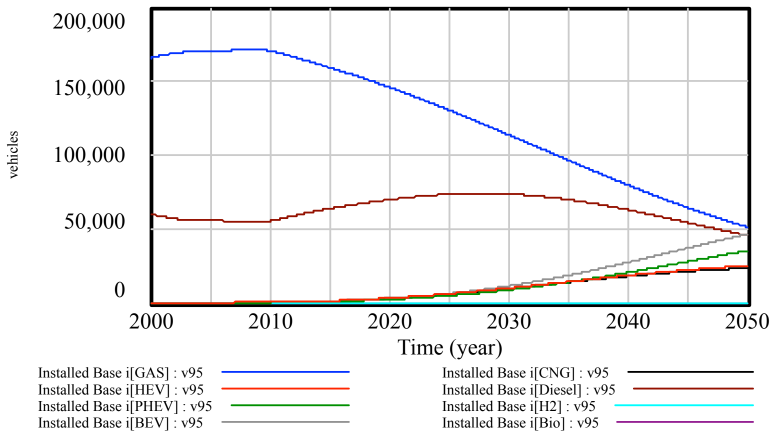

Figure 11: EV Case - Total number of vehicles

The charging time for BEV vehicles is greater than the refueling time for gasoline vehicles which increases the utility of charging stations and leads to more charging station. Charging time for BEV platform reduces through the simulation but is considerably less than for other platforms. The charging time partially explaines the higher number of charging stations over gasoline pumps. The range of BEV platform also has an affect on the utility of the charging stations. The range does not improve much over the simulation due to lack of fuel efficiency improvements. The lack of range improvements causes increased station utility which leads to more charging stations. The current state of the DtF model does therefore not capture the range improvements which can be expected when recent improvements are considered [63].

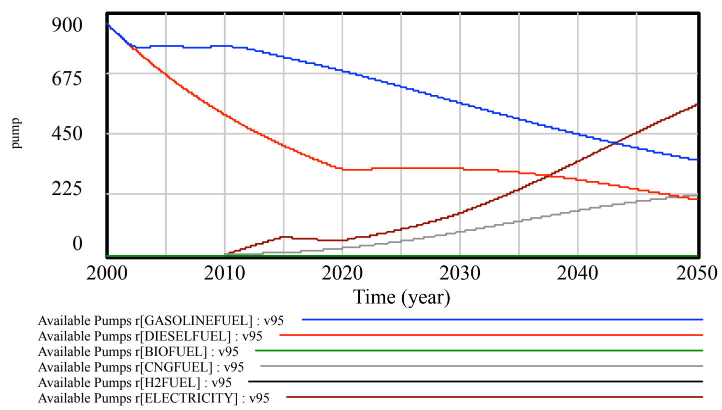

Figure 12: EV Case - Available Pumps/Charging stations for Vehicle Platforms

The total emission over the simulation time can be seen in Figure 13. The total emission does not change much from the base case, total of 25.7M tonne CO_2 and the annual emission at the end of simulation reduces by 32% from the 2000 value. The emission reduction from the base case is only 2% even with electricity and methane emission as zero. The EV case implies that establishing more initial stations could speed up the adoption of BEV vehicles but it does not help enough to reduce emissions. The small difference in emission reduction between the EV case and Base case is partially explained with the total reduction rate in the Base case. The total reduction rate in the Base case is very high because the model decreases the number of GAS and diesel vehicles to increase the number of AFVs. If the model assumed an expansion in the vehicle fleet the GAS and diesel platforms would likely not decrease as quickly as can be seen in the Base case and more emission reduction could be seen between cases.

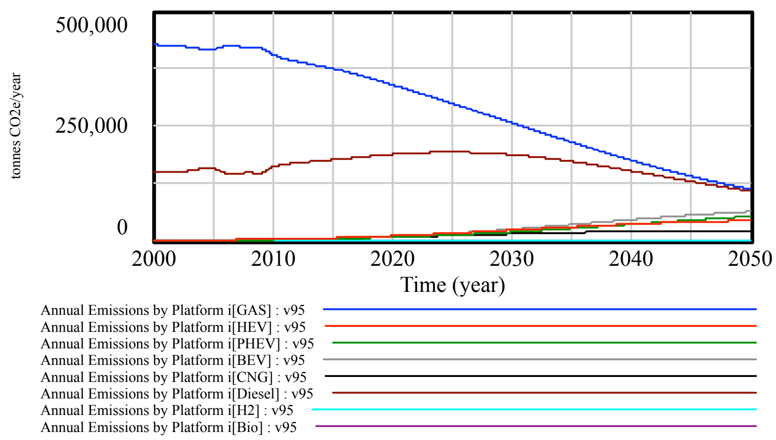

Figure 13: EV Case - Annual Emissions from Vehicle Platforms

6.3 CNG Case

In the CNG case additional market spending for CNG platform is $150M and exogenous stations added are five stations over a five year period, as shown in Table 8. All other additional spendings are the same as in the Base case.

Table 8: Additional Marketing Cost and Refueling Stations added for CNG Case

		HEV	PHEV	BEV	CNG
CNG Case	Marketing	$100M	$50M	$30M	$150M
	Stations	0	0	2 [a]	5 [a]

[a] Stations per year for five years.

The CNG share increases to little over 34.000 vehicles but that is not enough to take a leading part of the AFVs as can be seen in Figure 14.

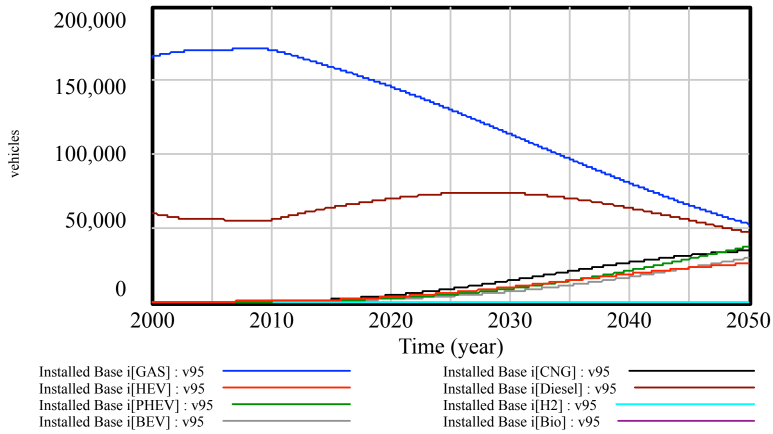

Figure 14: CNG Case - Total number of vehicles

PHEVs have a bigger share that could imply that CNG vehicles would not be a good candidate as a platform to subsidize if only one platform is to be supported. It should be noted that most CNG vehicles in Iceland have both gasoline and methane tanks which increases their range considerably. If the model was formulated to take the increased range into account the utility function for CNG platform would improve and lead to a larger installed base of CNG vehicles.

The number of CNG pumps increases with larger installed base, as can be seen in Figure 15. The fuel consumed by the CNG platform has an affect on the available pumps. The CNG fuel consumed at the end of simulation is 809 PJ/year where the potential methane production in Iceland is 1.72 PJ/year [14]. The DtF model does not assume any restrictions on production of fuel and therefore the number of pumps increases uninhibited. Since most CNG vehicles in Iceland have both CNG and gasoline tank the CNG fuel con-

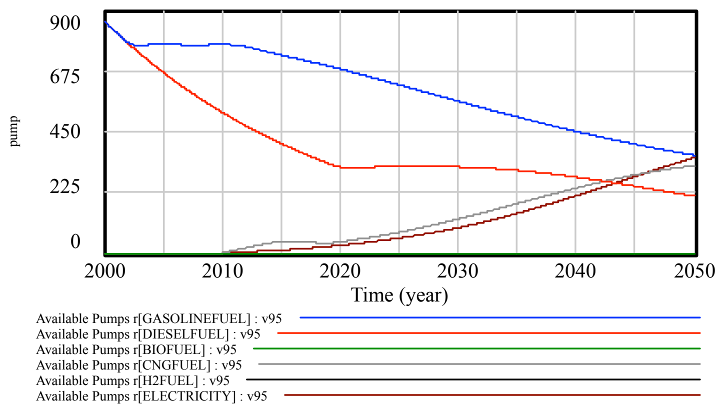

Figure 15: CNG Case - Available Pumps/Charging stations for Vehicle Platforms

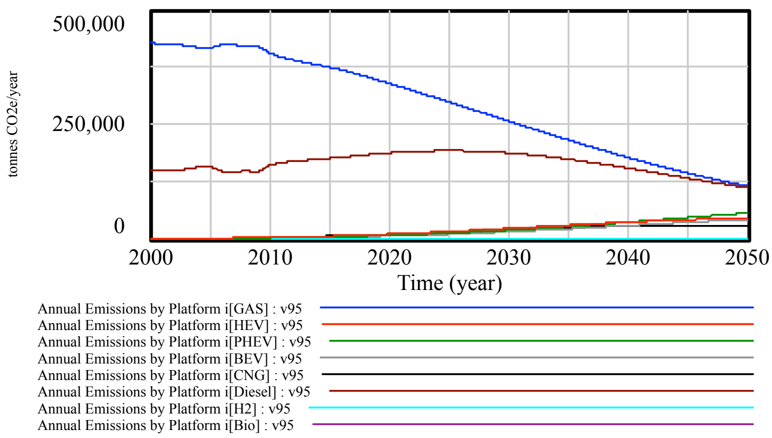

Figure 16: CNG Case - Annual Emission from Vehicle Platforms

sumed is likely overestimated by the DtF model. The restriction on production of methane would hinder the installed base of CNG vehicles and the number of pumps.

The annual emissions from each platform can be seen in Figure 16. The total cumulative emissions for the CNG scenario is 25.7M tonne CO_2 and gives, as for the EV scenario, a reduction of 32% from the 2000 value. Even though the CNG share is smaller than BEVs in the EV case the total emissions over the timeframe is the same.

6.4 H_2 Case

For the H_2 case, the only changes from the base case are additional spending on marketing of $150M for the H_2 platform, a $15.000 incentive for vehicle purchase and 5 exogenous stations per year for 5 years, as shown in Table 9.

Table 9: Additional Marketing Cost and Refueling Stations added for H_2 Case

		HEV	PHEV	BEV	CNG	H_2
H_2 Case	Marketing	$100M	$50M	$30M	$100M	$150 [a]
	Stations	0	0	2 [b]	1 [b]	$5 [b]

[a] And a $15.000 incentive for H_2 vehicle purchase
[b] Stations per year for five years.

The additional marketing and vehicle subsidies help to establish share of H_2 despite the high price of H_2 as can be seen in Figure 17. The H_2 vehicle price reduces through the simulation which helps increase the installed base. The total installed base of H_2 never reaches the other AFV platforms which could imply, like for the CNG case, that H_2 is not a good candidate for subsidies of only one platform is chosen.

The available pumps of H_2 increases through the simulation, as can be seen in Figure 18. The cost of construction is assumed zero for the Icelandic case but the cost does affect the available pump evolution. The cost of construction of a new H_2 station is considerably more expencive than for gasoline [15]. The cost of construction of H_2 refueling infrastructure would hinder the available pumps.

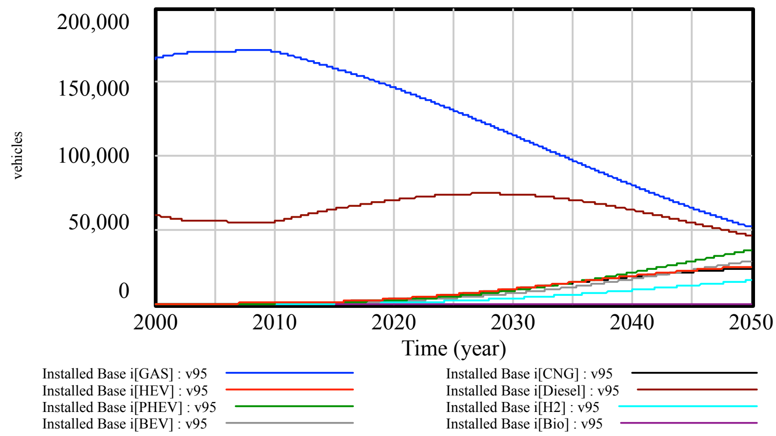

Figure 17: H_2 Case - Total number of vehicles

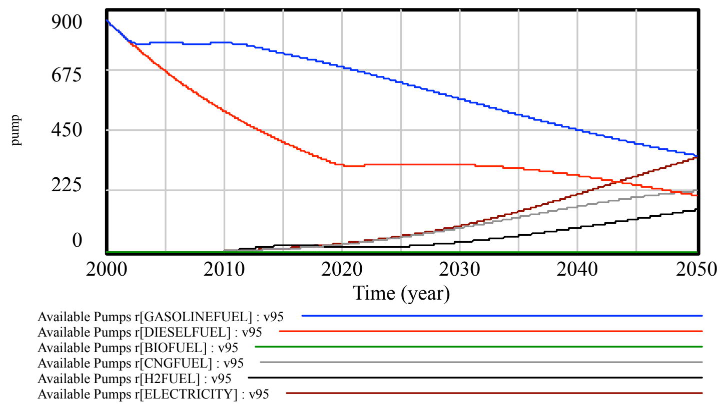

Figure 18: H_2 Case - Available Pumps/Charging stations for Vehicle Platforms

The total annual emissions for each platform can be seen in Figure 19. The total cumulative emissions is 25.72M tonne CO_2 which is a decrease of almost 33% from the 2000 values.

6.5 All AFV Case

The all AFV case includes additional spendings, incentive values and exogenously added stations for CNG, EV and H_2 like in other cases. The values can be seen in Table 10.

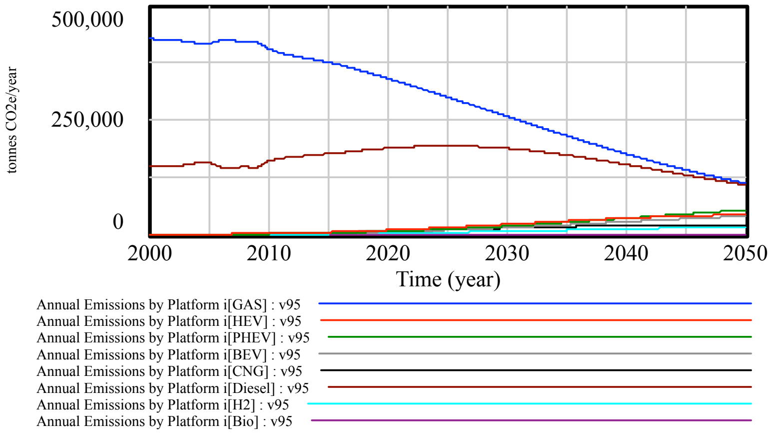

Figure 19: H_2 Case - Annual Emission from Vehicle Platforms

Table 10: Additional Marketing Cost and Refueling Stations added for All AFV case

		HEV	PHEV	BEV	CNG	H_2
H_2 Case	Marketing	\$100M	\$50M	\$50M	\$150M	\$150 [a]
	Stations	0	0	15 [b]	5 [b]	\$5 [b]

[a] And a \$15.000 incentive for H_2 vehicle purchase
[b] Stations per year for five years.

The share of each platforms when all have incentives are shown in Figure 20. BEV platform takes the lead and gets the largest share of all the AFV platforms. The BEV platform almost succeds to catch the diesel share. The AFV platforms succeed in reaching larger installed base than gasoline and diesel platforms together.

The total available pumps for CNG and CO_2 increases with the installed base as shown in Figure 21. The number of charging stations increase rapidly and even surpasses number of both gasoline and diesel pumps. Soon after the introduction of exogenous stations the DtF model reduces the number of pumps. The utility and profit of pumps is low and a larger installed base is required to increase the number again. This could imply that if all AFV platforms are subsidized, the number of exogenous pumps can not be to many.

The total cumulative emission is 25.4M tonne CO_2 and a total reduction of 35.4 % from the 2000 value, giving the most reduction of all cases. This scenario suggests that in order to reduce emissions, all AFVs should be supported.

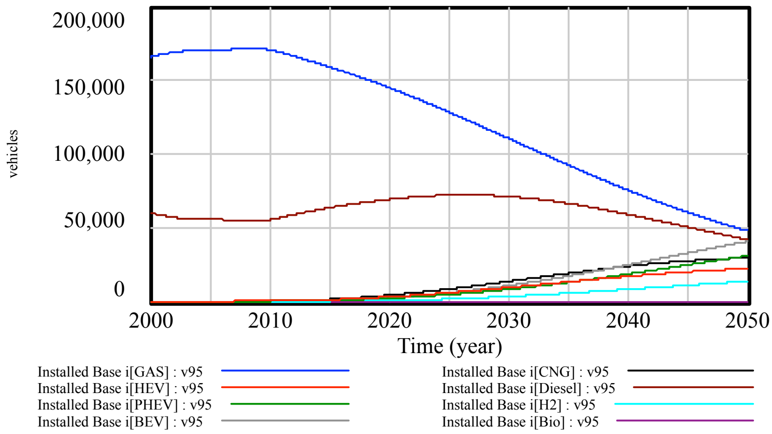

Figure 20: All AFV Case - Total number of vehicles

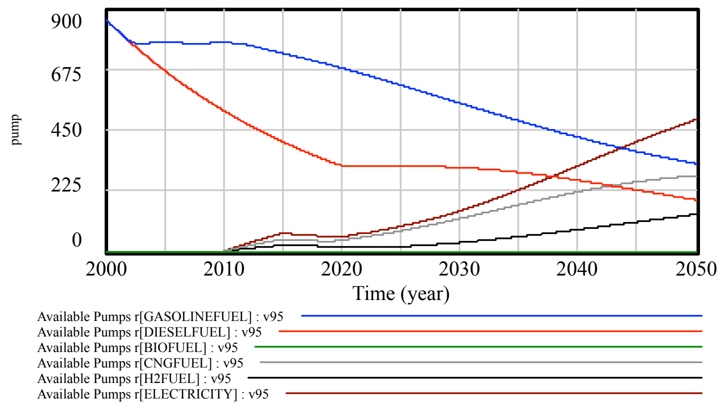

Figure 21: All AFV Case - Available Pumps/Charging stations for Vehicle Platforms

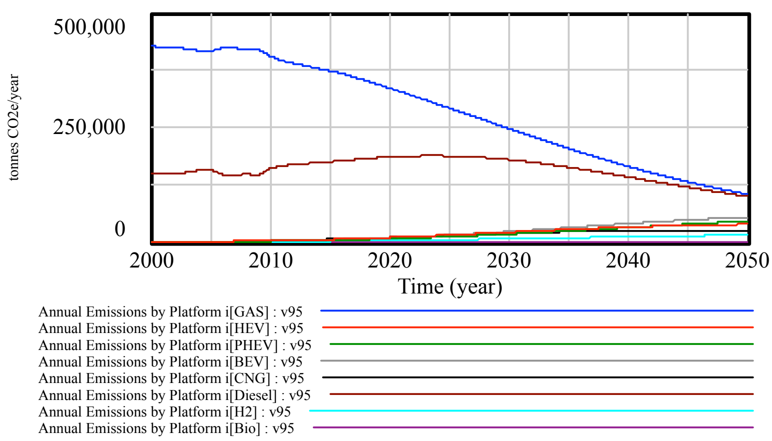

Figure 22: All AFV Case - Annual Emission from Vehicle Platforms

6.6 Summary

Total installed base from all scenarios can be seen in Table 11. The incentives have an effect on the total installed base of platforms which implies that increasing marketing and adding stations could help in the transition from fossil fuel vehicles.

The total cost of each reduced tonne from the scenarios are shown in Table 12. The values for the Base case are set to zero and total marketing cost and emission reduction are used for comparison. The cost of each tonne CO_2 for the EV scenario is least but the most expensive tonne CO_2 is in the H_2 scenario. The scenario where all AFV are in competition with each other the cost is $13.600 per tonne CO_2 but for EV case each tonne costs $4.200. The results imply that if emissions are to be reduced, all AFVs should be subsidized but it will come at a high price.

Table 11: Total Number of Vehicles from different scenarios

Platform	**Base Case**	**EV Case**	**CNG case**	**H_2 Case**	**All AFV case**
GAS	54.300	51.300	52.800	51.700	47.900
HEV	27.100	24.800	25.700	25.100	22.100
PHEV	39.400	35.100	37.000	36.000	30.800
BEV	31.300	46.300	29.300	28.600	40.400
CNG	25.500	23.100	34.400	23.500	29.300
Diesel	48.500	45.500	46.900	45.900	42.000
H_2	0	0	0	15.300	13.500

Table 12: Total Cost of Emissions Reduction

	Additional Cost [M$]	**Total Emission Reduction [tonnes CO_2]**	**Cost per tonne CO_2 [$/tonne]**
Base Case	0	0	0
EV Case	800	190.000	4.200
CNG Case	2.000	230.000	8.700
H_2 Case	5.250	220.000	23.900
All AFV Case	8.050	590.000	13.600

Chapter 7

Discussion

The results presented in this paper imply that marketing and more available pumps/charging stations can help in increasing the AFV share. The results also imply that more can be done in reducing emission since the scenarios show more decreased emission for AFV scenarios than in the Base case. It seems that a competition between AFV platforms is a good thing for reducing emission as the results from All AFV case shows. The increase in additional marketing for BEV platform, from the value in the Base case, was lower in the EV case than e.g. for CNG in the CNG case. Even so, the emission decrease in the EV case was close to the emission decrease in the CNG and H_2 case. The small difference in emissions decrease could suggest that the BEV platform could be a good canditate to subsidize since the cost of each tonne reduced is cheapest for the EV case. The amount spent on additional marketing needs more exploration, for example to see effect of same increased value of marketing for different scenarios. The effect of additional marketing without exogenously adding stations would also be interesting to explore.

The results presented in this paper are preliminary result since there are many simplifications and assumptions made. The next steps would be to adjust the DtF model better to Iceland. The cost of construction of refueling stations is set to zero to simplify the model but the cost of construction affects the station profits. The cost of constructing a H_2 station is more expensive than e.g. a gasoline station but cost of a charging station is considerably less expensive [15]. Therefore the results for available pumps/charging stations are distorted. The ancillary revenue was also set to zero but in order to take the DtF model to the next level it is important to make a thorough study on the cost and revenues to get more reliable results.

The DtF model uses the area of the country to find average distance between stations. In Iceland this formulation does not apply, at least not while there are few refueling stations. When new platforms are introduced in Iceland, the refueling infrastructure grows slowly in the capital area before stations are added outside the capital area. In Iceland the methane infrastructure has grown first in the capital city and then a station was added in Akureyri. The initial infrastructure grows in the capital area because the population in the capital area is 2/3 of the total population of Iceland [64]. For example, if there is only one or two refueling stations the average distance to a station is very high. The average distance is therefore overestimated by the model because the average distance between the first few stations would most likely be less. In Iceland the vehicle miles travelled per year for methane vehicles would be less than assumed in this paper because having stations only in the capital area limits out of town driving.

The DtF model assumes that methane vehicles run on methane alone but in Iceland most methane vehicles in Iceland have both methane and gasoline tanks. The vehicle empties the methane tank and then switches to gasoline. To adjust the DtF model more to Iceland it would be preferable to add a methane/gasoline platform. The added methane tank has an affect on the range of the platform which distorts the results.

The DtF model is formulated so that total vehicle sale of each platform has affect on the fuel efficiency improvements. For Icelandic numbers in the model the total vehicle sales are so little that almost no effect can be seen. The fuel efficiency affects the emission of the platforms and the fuel consumed. The total emissions could therefore be overestimated by the model. The fuel consumed affects the number of available stations and therefore the available stations could also be overestimated. The model could be improved for Icelandic situation by formulating the fuel efficiency improvements in such a way that the total sales does not affect the improvements. The learning curve for fuel efficiency improvements for the US case should be used indicate how fuel efficiency could improve over the simulation time. The vehicle price is also affected by the total sales. The results for the US case could also help formulating the vehicle price without effects from total sales. Iceland has very little effect on the OEMs and therefore the formulation for OEM should be cut or at least changed.

The assumption that the total vehicle fleet stays constant needs to be changed to adjust the model better to Iceland. A total of 35% increase in vehicle fleet in Iceland is expected until the year 2050 [28]. The gasoline and diesel decrease in installed base is likely to quick considering the expected fleet growth. If an increase in total vehicle fleet was formulated into the DtF model, gasoline and diesel platforms would likely not reduce as much as results imply when AFVs get a larger share.

One drawback of the DtF model is the timeframe. The timeframe used in the DtF model is from 2000-2050. The results from the first eleven years of the simulation can be used to compare to real data to validate the model. In the model the year 2010 is hardcoded into some equations so to change the timeframe of the simulation the user needs to go through all equations to change the year 2010 to a preferable year. The model needs to be generalized better and give the user more option to control the timeframe.

Chapter 8

Conclusion

In the paper we present a system dynamics simulation model that was used to explore the diffusion of alternative fuel vehicles in Iceland. The model captures the coevolution of total installed base of vehicles from different platforms and the refueling infrastructure. The results imply that emission reduction in the transport sector can be achieved with incentives to consumers and fuel supply infrastructure. The results suggest that offering incentives for all alternative fuel vehicles could help decrease emission more than if only one platform were subsidized but it will come with a high price. The battery electric vehicle platform excels other alternative fuel vehicles when it comes to cost per reduced tonne CO_2. In Iceland there are incentives to help vehicles with low emission rate but these insentives also apply to gasoline and diesel vehicles with low emission rates. The task of reducing emission from the transport sector is difficult. The current incentives are not aimed at making way for AFVs and more can be done to reduce emission. Selecting one platform to subsidize would likely be preferable for Iceland. Icelands area is large but the population is low. Installing two or even three types of platform infrastructure around the country would not necessarily be profitable for all due to many areas with very low population. The results imply that the BEV platform is the most realistic platform to subsidize since the cost of emission reduction is lowest in the EV case. It is important to conduct more study how a reduction in emission can be achieved and react accordingly.

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Appendix A

Acronyms

Acronym	**Variable Name**
DtF	Driving the Future
AFV	Alternative Fuel Vehicle
ICE	Internal Combustion Engine
GAS	Gasoline vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Electric Vehicle
BEV	Battery electric Vehicle
CNG	Compressed Natural Gas
H_2	Hydrogen
OEM	Original Equipment Manufacturer
MSRP	Manufacturer's Suggested Retail Price
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GGE	Gasoline Gallon Equivalent
R&D	Research and Development
VMT	Vehicle Miles Travelled

Appendix B

Model Code

Cumulative Marketing= INTEG (Total Annual Marketing,0)
∼ million

Cumulative market spending is total market spending cumulative over simulation time with initial value of zero.

Retail Electricity Price = Conventional Electricity Price
∼ cents/(kW*hour)

Conventional electricity price is a variable that joins the variables "Electricity price till 2011" and "Electricity price after 2011"

GHG Emissions Factor Electricity GGE = "GHG Emissions Factor - Electricity" · Native units to GGE electricity
∼ tonnes CO2e/GGE

"GHG emission factor-Electricity" is emissions per kWh and a conversion factor is multiplied to the factor to convert to emission per GGE.

Vehicle Price j[TechnologyTo]= Initial Vehicle Price j[TechnologyTo]*(1-Vehicle Price Reduction Rate j[TechnologyTo])^power[TechnologyTo] ∼ $/vehicles

Vehicle price is initial vehicle price, chosen by model user times a reduction rate.

power[TechnologyTo]= IF THEN ELSE(Platform Introduced j[TechnologyTo] = 0,0 , Time-Platform Introduction Date j [TechnologyTo]) ∼ dmnl

IF THEN ElSE(Platform Introduced j) is to make sure that the platform has entered the market. Power to calculate t - t_0 *for each platform*

Appendix C

Icelandic Data Summary

Data	Value	Company	Source
Number of charging station	10	Orka Náttúrunnar	[1]
Number of methane stations	5	Metan hf.	[2]
Policies on vehicle excise taxes	0% for vehicles with 0-80 g/km emission [a]	Tollstjóri	[3]
Policy that ensures free parking for vehicles who emit less than 100g/km	Free parking for 90 min. for vehicles with less than 100 g/km emission	Reykjavíkurborg	[4]
Share of renewable energy	99%	Orkustofnun	[24]
Forecast for platform expansion from 2015-2050	35%	Vegagerðin	[28]
Total vehicle installed base	226.321 vehicles	Samgöngustofa	[29]
Effective area	25%	Vísindavefur	[41]
Median household income	31.500 $/year [b]	Viðskiptablaðið	[42]
Cost of home charger	2000 $	IslandusBílar	[45]
Laws on gasoline taxes and methane, ethanol and H_2 exclusion from taxes	66.9 ISK/L. gasoline	Alþingi	[51]
Laws on diesel taxes	57.4 ISK/L. diesel	Ríkisskattstjóri	[52]
Laws on carbon tax	5 ISK/L gasoline	Alþingi	[53]

[a] Values dependent on emission rate.
[b] With 2% income growth.

Missing in the table is initial vehicle price that can be found in Table 4.

Data	**Value**	**Company**	**Source**
Station Markup	13%	Morgunblaðið	[55]
Available gasoline and diesel stations in 2016 and number of pumps per station	287 station, avg. 3 pumps	Fuel Companies	[56, 57, 58, 59, 60, 61]
Total vehicle marketing 2005	500M ISK	Morgunblaðið	[62]
Population in the capital area	2/3 of total population	Hagstofan	[64]

Year	Gasoline $/gallon	Diesel $/gallon	Methane $/GGE	Electricity cents/kWh	H_2 $/kg
2000	2.55	1.11	2.17	5.6	5
2001	2.75	1.33	2.17	6.21	
2002	2.68	1.37	2.17	6.82	
2003	2.86	1.36	2.17	7.43	
2004	2.94	1.2	2.17	8.04	
2005	3.05	1.58	2.17	8.65	
2006	3.38	3.3	2.38	9.25	
2007	3.38	3.42	2.38	9.86	
2008	4.16	4.2	2.38	10.47	
2009	4.35	4.89	2.38	11.08	
2010	5.95	5.91	2.87	11.69	
2011	6.47	6.39	3.25	12.3	6.75
Source	[46]	[47]	[47]	[48, 49]	[50]

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