ABSTRACT

Rapid growth in population and increase in disposable income has led to a robust increase in automotive sales in India. As in many parts of the world, the internal combustion engines are the dominant vehicle power train in India. This has led to increase in tailpipe emissions in congested cities as well as increased consumption of crude oil. India needs to devise effective strategies to introduce fuel efficient nonpolluting Alternative Fuel Vehicles (AFV) to reduce GHG emissions and reduce oil consumption. In 2013, the Government of India unveiled a National Electric Mobility Mission Plan to promote AFV sales in India in a coordinated manner. Many similar, well-intentioned programs have been tried in the past. However, the creation of sustainable AFV markets has remained a challenge. This work presents the development of a multiplatform system dynamics model that helps one explore the dynamics of adoption of AFVs in Indian context. Using the model we explore three unique policy scenarios where the adoption of AFVs is studied. We show that the successful AFV adoption is dependent not just on providing demand side incentives, but also on promoting the creation of the refueling infrastructure. Results also show that Plug in Hybrid Electric Vehicle has the potential to be the dominant alternative fuel vehicle platform in India provided effective policies are in place.

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Title: Jay W. Forrester Professor of Management, Director, MIT System Dynamics Group
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1. Introduction

Indian passenger car market has recorded a Compounded Annual Growth Rate (CAGR) of 15.11 % (Heavy Industry and Public Enterprises, 2013, p. 21) over the last 5 years. It is projected to grow to 10 million vehicles a year by 2020. This explosive growth is fueled primarily by three factors: increase in disposable income among the Indian middle class, population growth, and urbanization. Figure 1 below illustrates the total number of registered cars in India from 1980 to 2011. One can see that, the growth of vehicles strongly coincides with the growth in the GDP per capita of the country.

Figure 1: Total Number of Registered Cars and GDP Per Capita PPP (Ministry of Road Transport and Highways, 2009 -2010 & 2010-2011)

While this growth augurs well for the Indian economy, it has also led to increasing pollution in the congested cities and rising greenhouse gas emissions. Because the dominant power train in India is petrol based internal combustion engines, growth in the vehicle population coupled with increased
vehicle kilometers travelled per year has also led to a sharp increase in consumption of petroleum based fuels. Since India meets most of its oil needs through imports (85% (Ministry of Heavy Industry and Public Enterprises, 2013, p. 14)), an increased consumption of petroleum based fuels leads to greater pressures on Indian foreign exchange reserves and energy security.

Despite efforts to explore ways to promote environmentally friendly alternative fuel vehicle (AFV), policy makers and the automobile industry have found the task of developing sustainable markets for expensive alternative fuel vehicles in a developing economy like India a challenging task. The picture is not different elsewhere; world over there have been numerous failed attempts to establish sustainable AFV markets (Knie, 2001) (Flynn, 2002). The automotive market is a complex system with multiple stakeholders like the government, environmental agencies, automotive OEM, refueling Infrastructure owners and consumers. Prediction of system emergence becomes even more difficult with the introduction of new power trains. Because of the complexity of the system, policy makers and automotive OEM need models and analytical tools to study the dynamics of adoption of AFVs. To the best of our knowledge, currently, there are no models to explicitly explore the high leverage policies that can be used to understand the AFV adoption strategies in India. This thesis attempts to bridge the existing gap by developing a multi-platform system dynamics model of the Indian automotive sector.

Following the Introduction, we describe the model formulation in chapter two. The model captures the interactions among consumer choice, OEM capacity and refueling infrastructure to estimate the vehicle sales, total emissions and number of refueling stations for each of the power trains considered. The third chapter reports the results of simulations performed using this model. Various policy and growth scenarios are explored. The final chapter presents the limitations of the current model and future research directions followed by conclusions.
2. Model Formulation

In past a number of authors (Jeroen Struben and John D Sterman, 2008) (Keith, 2012) have used system dynamics approach to evaluate the adoption of alternative fuel vehicle (AFV) technologies in automotive sector. The present work builds on the model developed by David Keith (Keith, 2012) to study the evolution of HEVs in the US market. Figure 2 describes briefly the salient points of the AFV introduction model. The total installed base of vehicles in a given platform is a stock that increases with the vehicle sales and decreases with vehicles discard. Vehicle sales are impacted by the demand for a given platform, which in turn is affected by new buyers and people seeking to replace the discarded vehicles. However, the share of the vehicle buyers choosing a given platform is dependent on the consumer’s affinity towards that platform. Consumer’s affinity to a platform is affected by the utility of the platform and the familiarity of the platform. Increase in vehicle sales of a given platform, encourages increase in marketing efforts for the platform, thereby leading to increase in familiarity of the platform. Familiarity also builds, based on the word of mouth publicity that is received from drivers and non-drivers of the platform. This forms a reinforcing familiarity accumulation loop. The utility of the vehicle is simply modeled as a weighted average of the acquisition price, operating cost, refueling cost, acceleration, top speed, emissions and the scope of vehicles in a given platform. The acquisition price is modeled to reduce based on the learning from each platform. This forms a reinforcing learning-by-doing loop that affects the consumer choice. Finally, increase in installed base of vehicles lead to increase in fuel demand thereby creating need for refueling infrastructure. The increase in refueling infrastructure lead to reduction in wait times at the fueling point as well as reduce the out of fuel risk (range anxiety); thereby reducing the refueling cost. This is the standard, infrastructure co-evolution loop that is widely discussed in AFV introduction literature (Jeroen Struben and John D Sterman, 2008) (Supple, 2007).

The current model extends Keith model in 3 specific ways. Firstly, since this model is used to study Indian automotive market where the passenger car market has been growing, we have built in structure
to capture the dynamics of this expansion of the total passenger car market. Secondly, Keith model captures the dynamics of consumer choice between four vehicle technologies (Gasoline, HEV, BEV and PHEV). We have extended the model to eight vehicle technologies: Gasoline (GAS), Diesel (DES), Biofuel (BIO), Battery Electric Vehicle (BEV), Plug in Hybrid (PHEV), Hybrid Electric Vehicle (HEV), Compressed Natural Gas Vehicle (CNG) and Hydrogen powered fuel cell vehicle (H2). Thirdly, we have a more detailed formulation to capture the dynamics and economics of the refueling infrastructure for each of the power trains.

The model thus developed can be used to forecast the evolution of the installed base of each of the technology platforms. Thereafter, one can easily estimate the “well to wheel” emissions of the entire fleet by taking the product of the emissions per year of one vehicle of a technology platform and the total fleet size.

At this stage we present, the key assumptions of the models. Firstly, the model assumes a homogenous consumer across the country with average preferences and buying capacity. In general it has been observed that the VKT is a function of the economy. However this model, for sake of simplicity, assumes that the Vehicle Kilometers Travelled increases at a constant rate from 100 km per year irrespective of the economic condition. The model also assumes that the supply of fuel to the refueling infrastructures is not constrained. Fuel is assumed to available on demand, with prices increasing at a constant rate. Lastly, the model also assumes that there is no substantial information asymmetry for the consumer as well as for the owners of refueling infrastructure.

**Total Installed Base Expansion**

As mentioned in the previous section, it is important to estimate the overall demand for vehicles in India. Historically there has been a strong correlation between GDP per capita and the total installed
base of vehicles in a given country. Also the total installed base is a function of the population. India has in recent years seen a steady increase in both GDP per capita and population. A projection of the total desired installed base of vehicles is made using S- Shaped Logistic Function.

\[
V_t^* = \frac{\gamma \times V_{init} \times e^{\left(\alpha \times \frac{GDP_t}{TCO} - \beta\right)}}{\gamma + V_{init} \times e^{\left(\alpha \times \frac{GDP_t}{TCO} - \beta\right)}} \quad \text{Units: (Vehicles/person)} \quad (1)
\]

Where \( V_t^* \) is the total desired installed base in year \( t \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )</td>
<td>35</td>
<td>dmnl</td>
<td>Saturation percentage</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>12.6</td>
<td>person/vehicle</td>
<td>Constant</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.3</td>
<td>dmnl</td>
<td>Constant</td>
</tr>
<tr>
<td>( GDP_t )</td>
<td>Table Function</td>
<td>$/person</td>
<td>Gross Domestic Product in $ purchase parity (The World Bank, 2013)</td>
</tr>
</tbody>
</table>

Table 1: Values of Parameters for Gompertz Function

Parameters in Table 1 represent the preliminary values. However the model specific values are parameterized by performing a sensitivity analysis as shown in chapter 3.

TCO is the Total Cost of Ownership of vehicle which is calculated as a sum of Purchase price ($/vehicles) and a Net present value of Operating Cost ($/vehicles). A constant discount rate of \( dr \) % is used in the NPV calculation.

The Total Installed Base in the year \( t \) given by \( \rho_t \)
\[ \rho_t = \frac{\sigma}{1000} \times V_t \]  
Units: (Vehicles)  \hspace{1cm} (2)

Where \( \sigma \) is the stock of population. Population growth and GDP growth are estimated based on the UN data (United Nations, 2013) and IMF data (International Monetary Fund, 2013) respectively. The Installed base of each of the technology platform is then estimated based on the projected market share of each of the platform from the vehicle choice model described in the next section.

\[ \rho_{tj} = \rho_t \times \tau_j \]  
Units: (Vehicles)  \hspace{1cm} (3)

Where Projected Market Share of platform \( j \) is given by \( \tau_j \), as determined by consumer choice.

The total demand for a platform is sum of platform demand due to market expansion and platform demand due to vehicle discards. Vehicle discards is modeled using a standard ageing chain (Sterman, 2000) of the installed base as described in the fleet turnover model (Keith, 2012).

**Consumer Choice Model**

The dynamics of competition between various fuel technologies are shown in the causal loop diagram in Figure 2. As illustrated, the stock of vehicles (installed base) of a given platform increases with vehicle sales and decreases with vehicle discard. Vehicle sales are affected by the number of consumers choosing the platform. A consumer chooses a given platform based on two factors. The first factor is the utility of the vehicle in the given market. The utility is a function of vehicle price, operating cost, range, top speed acceleration and model breadth (scope). The cost of a vehicle reduces as vehicle sales increases because of economies of scale. Increased investment in R&D and efficiencies of learning by doing further reduce vehicle cost. Apart from these power train technology specific parameters the vehicle utility is also affected by co evolution of refueling infrastructure. Increase in the number of refueling stations reduces the range anxiety and the wait times thereby increasing the utility of a vehicle platform. The second important factor affecting the consumer affinity to a platform is the consumer's
familiarity with the platform. Consumer familiarity is increased by both word of mouth and the marketing efforts of the automotive companies.

Figure 2: Platform Competition Model Overview

Figure 3: NMNL Decision Making Structure
A nested multinomial logit (NMNL) decision structure in Figure 3 captures the consumer choice among the available technologies (Train, 2009). Affinity of a person currently using platform $i$ to platform $j$ is given by:

$$A_{ij} = e^{U_j} \times F_{ij}$$

Units: Dimensionless  \hspace{1cm} (4)

$\forall i, j \in \{\text{GAS, DES, HEV, BIO, CNG, H2, BEV, PHEV}\}$

Here, utility of a platform $j$ is given by $U_j$ and the Familiarity of platform $j$ for a person who is currently using platform $i$ is given by $F_{ij}$.

$$I_{ICE} = \ln \left( e^{\frac{A_{iGAS}}{\lambda}} + e^{\frac{A_{iDES}}{\lambda}} \right); \quad I_{PLUG} = \ln \left( e^{\frac{A_{iBEV}}{\lambda}} + e^{\frac{A_{iPHEV}}{\lambda}} \right)$$

Units: Dimensionless  \hspace{1cm} (5)

$I_{ICE}$ and $I_{PLUG}$ are inclusive value of ICE Nest and PLUG Nest respectively. Share of each nest is given by Equation 6-10. Here $\lambda$ is nesting coefficient that symbolizes the inverse of the degree of correlation between the elements of the nest ($A \lambda$ value of 1 implies zero correlation).

$$\text{Share}_{ICE} = \frac{e^{\lambda \ln I_{ICE}}}{e^{\lambda \ln I_{ICE}} + e^{\lambda \ln I_{PLUG}} + \sum_j e^{\lambda \ln d_{ij}}}$$

Units: Dimensionless  \hspace{1cm} (6)

$\forall i, j = \{\text{CNG, BIO, H2, HEV}\}$
\[
\text{Share}_{\text{PLUG}} = \frac{\alpha x \ln \beta_{\text{PLUG}}}{\alpha x \ln \beta_{\text{ICE}} + \alpha x \ln \beta_{\text{PLUG}} + \sum_j \alpha x \ln \beta_{(A_j)}} \quad \text{Units: Dimensionless}
\]

\[\forall i, j = \{\text{CNG, BIO, H2, HEV}\} \quad (7)\]

\[
\text{Share}_{ij} = \frac{e^{\ln(A_{ij})}}{e^{\alpha x \ln \beta_{\text{ICE}}} + e^{\alpha x \ln \beta_{\text{PLUG}}} + \sum_j e^{\ln(A_{ij})}} \quad \forall i, j = \{\text{CNG, BIO, H2, HEV}\}
\]

\[\text{Units: Dimensionless} \quad (8)\]

\[
\text{Share}_{i,\text{GAS}} = \text{Share}_{i,\text{ICE}} \times \frac{e^{\ln(A_{i,\text{GAS}})}}{e^{\ln(A_{i,\text{GAS}})} + e^{\ln(A_{i,\text{DES}})}} \quad \text{; Share}_{i,\text{DES}} = \text{Share}_{i,\text{ICE}} \times \frac{e^{\ln(A_{i,\text{DES}})}}{e^{\ln(A_{i,\text{GAS}})} + e^{\ln(A_{i,\text{DES}})}}
\]

\[\text{Units: Dimensionless} \quad (9)\]

\[
\text{Share}_{i,\text{BEV}} = \text{Share}_{i,\text{PLUG}} \times \frac{e^{\ln(A_{i,\text{BEV}})}}{e^{\ln(A_{i,\text{BEV}})} + e^{\ln(A_{i,\text{PHEV}})}} \quad \text{; Share}_{i,\text{PHEV}} = \text{Share}_{i,\text{PLUG}} \times \frac{e^{\ln(A_{i,\text{PHEV}})}}{e^{\ln(A_{i,\text{BEV}})} + e^{\ln(A_{i,\text{PHEV}})}}
\]

\[\text{Units: Dimensionless} \quad (10)\]

**Refueling Infrastructure Economics and Co-Evolution**

Any AFV technology, in order to become sustainable, must overcome the chicken and egg problem associated with the co-evolution of refueling infrastructure. If there is no ubiquitous refueling infrastructure, the range anxiety increases and the cost of refueling becomes high. However, if consumption of fuel is not significant owing to small installed base, then there is no economic incentive to construct new refueling stations. In order to determine a sustainable intervention that helps a technology break out of this vicious loop, one needs to model the economics of a refueling station in detail.
Figure 4 shows the mapping between power train technologies and fuel type and a mapping between fuel type and stations. As can be seen, in the current model we model 4 types of refueling stations. They are Gas Station, Charging Station, CNG Station and H2 Station. A typical station consists of a collection of refueling pumps. Because of similarities in dispensing technologies, business owners generally construct Gasoline, Diesel and Bio fuel pumps in a single Gas station.

**Figure 4: Mapping of Power Train Technologies to Fuel Type and Station Type**

**Station Profitability Calculation**

In order to calculate the operating profits of a pump, we begin first by estimating the total fuel consumed by all vehicles using the specific type station/pump. We then estimate fuel consumed per pump by dividing the total fuel consumed by the total number of pumps available. Once the fuel consumed per pump is known, the operating profits is calculated by simply multiplying the fuel consumed by the mark up per gallon of fuel.

Fuel of type r consumed by vehicle of platform i ($Q_{ir}$) is calculated by Equation 11. Here $p_{ir}$ is the installed base of platform i using fuel r given in vehicles units. $v_{ir}$ is the vehicle miles traveled by one
vehicle in a year given in miles/vehicle/year units. \( \eta_{ir} \) is the fuel efficiency of the vehicle in miles/gallon units.

\[
\Omega_r = \frac{\pi_{ir} \times \eta_{ir}}{\eta_{ir}} \quad \forall \ i \in \{GAS, DES, BIO, HEV, BEV, PHEV, CNG, H2\} \quad \text{and} \quad \forall \ r \in \{Gasoline, Diesel, Cng, H2, Biofuel, Electricity\} \quad \text{Units: gallon/year}
\]

Total number of pumps of each fuel type \( \kappa_r \) (pumps) is determined by simply taking the product of available stations \( \phi_r \); pump mix in a given station \( \zeta_g \) and the number of pumps per station \( \chi_f \) as shown in Equation 12 below.

\[
\kappa_r = \phi_r \times \zeta_g \times \chi_f, \forall f \in \{GASPUMP, CNGPUMP, PLUG, H2PUMP\} \quad \text{and} \quad \forall g \in \{Gasolinepump, Diesel pump, Bio Fuel pump\} \quad \text{Units: pump}
\]

Calculation of fuel consumed at each pump \( \varphi_r \) (gallon/pump/year) is captured in Equation 13 where \( \varepsilon_r \) is the maximum fuel dispensing capacity of a pump.

\[
\varphi_r = \text{MIN}(\varepsilon_r, \frac{\Omega_r}{\kappa_r}) \quad \text{Units: Dimensionless}
\]

Once the fuel consumed per pump is known the operating profits per pump \( \pi_r \) ($/pump/year) is calculated by simply multiplying the profit margin per gallon of fuel \( \delta_r \) ($/gallon) with the fuel dispensed at the station and then subtracting the operating cost of the fuel, \( \alpha_r \) ($/gallon) as described in Equation 14.

\[
\pi_r = \varphi_r \times (\delta_r - \alpha_r) \quad \text{Units: $/pump/year}
\]

Once the profit per a pump is known, operating profit per station is simply the product of the profits per pump, pump mix per station and pumps per station. We then get the net profit per station, \( T_r \) ($/station/year) by adding the ancillary revenues per station per year, \( A_r \) ($/station/year) and subtracting the fixed cost \( K_r \) ($/station/year) amortized over the life of the station.
\[ T_f = \pi_r \times \varsigma_g \times X_f + A_f - K_f \quad \text{Units: } \$/\text{station/year} \quad (15) \]

**Gas Station Pump Mix Calculation**

An owner of a Gas Station is expected to make a decision on the mix of pumps based on the utility of a given pump type. Therefore the pump mix choice is modeled as a multinomial logit function based on the utility of the pump. The utility, \( U_r \), is a weighted sum of profit per pumps of a given fuel type, switching cost, \((SC_r)\) and the utilization level \((J_r)\) of the pump. Equation 16 below calculates the utility of a given pump.

\[
U_r = w_1 \times \pi_r + w_2 \times SC_r + w_3 \times J_r \quad \text{Units: Dimensionless} \quad (16)
\]

Desired gas station mix \( g \), \( D_g \) is given by

\[
D_g = \frac{e^{U_g}}{\Sigma e^{U_g}} ; \text{Where } g \text{ is a sub set of } r \quad \text{Units: Dimensionless} \quad (17)
\]
The rate of change of gas station pump mix \( R_g \) (Dimensionless/year) is simply the difference of the desired gas station pump mix and the current gas station pump mix over the time to change the gas station mix as shown in the Equation 18.

\[
R_g = \frac{D_g - \zeta_g}{\tau}
\]  
Units: Dimensionless/year  

The Gas Station Pump mix \( \zeta_g \) is stock that is calculated by integrating the rate of change of gas station pump mix \( R_g \) as shown in Equation 19.

\[
\zeta_g = \zeta_g(0) + \int R_g
\]  
Units: Dimensionless  

**Calculation of Available Infrastructure**

The Available Infrastructure stock is calculated by the standard stock management structure (Sterman, 2000) as shown in the causal loop diagram in Figure 6. The Order rate of new refueling infrastructure is a function of four parameters: Station loss rate, Station profitability, Station Utilization and Infrastructure under construction. The stock of available stations in increased with the rate of acquisition of new stations, \( A_f \) (station/year) and decreases with the station loss rate, \( I_f \) (station/year).

\[
\phi_f = \phi_f(0) + \int (A_f - I_f)
\]  
Units: Stations  

Infrastructure acquisition rate, \( A_f \) (station/year) and Infrastructure loss rate \( I_f \) (station/year) are calculated by the Equation 21 below. Where \( A_f \) the stock of Infrastructure in construction is, \( \phi \) is the time to install the infrastructure and \( b \) is the lifetime of the available infrastructure.

\[
A_f = \frac{\Lambda_f}{\phi} ; I_f = \frac{\phi_f}{b}
\]  
Units: station/year
The stock of infrastructure under construction, \( A_f \) (station) represents the delay between the decision to construct the infrastructure and the availability of infrastructure. It increases with the infrastructure order rate, \( O_f \) (station/year) and decreases at the rate the stations become available, \( A_f \) (station/year).

\[
A_f = A_f(0) + \int (O_f - A_f) \quad \text{Units: station}
\]  

Figure 6: Stock Management Structure for Infrastructure Availability

The order rate, \( O_f \) (station) is given by Equation 23 below.

\[
O_f = \text{MAX}(0, \left( \frac{\Phi_f - \Phi_f \times E_p \times E_f}{6} \right) + \frac{A_f}{6}) \quad \text{Units: station/year}
\]

\( E_p \) and \( E_f \) are the desired change in infrastructure because of profitability and utilization respectively.

Where, \( 6 \) represents supply line adjustment time. Both \( E_p \) and \( E_f \) are normalized table functions that reduce to 1 when the profitability and utilization are equal to target profitability and utilization.
respectively. The table functions used is plotted below in the Figure 7. Profitability of a station is the ratio of station profits and station costs. Utilization is the ratio of available stations and demand for stations and is calculated endogenously as given in Keith Model (Keith, 2012).

Figure 7: Effect of Profitability and Utilization on Desired Infrastructure
3. Model Parameterization and Scenario Analysis

The AFV model that is developed in this work needs to be calibrated to a given market and geographic region. I begin by first establishing the attributes of vehicles pertaining to each platform. For the platform which is already introduced in Indian market, I use the most popular vehicle as the representative vehicle. However for the platforms that are yet to be introduced, the values are taken based on my best estimate. Table 2 below shows the assumptions for vehicles of each platform.

<table>
<thead>
<tr>
<th>PLATFORM</th>
<th>Battery (kWh/Vehicle)</th>
<th>Tank Capacity (GGE)</th>
<th>Initial Fuel Efficiency (miles/GGE)</th>
<th>Energy Efficiency (kWh/miles)</th>
<th>Acceleration (0-30 mph)</th>
<th>Top Speed (miles/hour)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS</td>
<td>0</td>
<td>11.35</td>
<td>30</td>
<td>N/A</td>
<td>3.6</td>
<td>100</td>
<td>(Maruti Suzuki, 2013)</td>
</tr>
<tr>
<td>DIESEL</td>
<td>0</td>
<td>9.8</td>
<td>38</td>
<td>N/A</td>
<td>4.5</td>
<td>95</td>
<td>(Maruti Suzuki, 2013)</td>
</tr>
<tr>
<td>PLATFORM</td>
<td>Battery Capacity (kWh/Vehicle)</td>
<td>Tank Capacity (GGE)</td>
<td>Initial Fuel Efficiency (miles/GGE)</td>
<td>Energy Efficiency (kWh/miles)</td>
<td>Acceleration (0-30 mph)</td>
<td>Top Speed (miles/hour)</td>
<td>Source</td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------</td>
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<td>-------------------------------------</td>
<td>-------------------------------</td>
<td>--------------------------</td>
<td>------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>PHEV</td>
<td>12.8</td>
<td>9</td>
<td>95</td>
<td>0.2</td>
<td>4</td>
<td>95</td>
<td>(Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid Electric, 2012, p. 157)</td>
</tr>
<tr>
<td>BEV</td>
<td>20</td>
<td>N/A</td>
<td>100</td>
<td>0.2</td>
<td>3</td>
<td>50</td>
<td>(Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid Electric, 2012, p. 157)</td>
</tr>
<tr>
<td>CNG</td>
<td>0</td>
<td>11.35</td>
<td>30</td>
<td>N/A</td>
<td>4.5</td>
<td>90</td>
<td>(Maruti Suzuki, 2013)</td>
</tr>
<tr>
<td>PLATFORM</td>
<td>Battery Capacity (GGE)</td>
<td>Tank Capacity (miles/GGE)</td>
<td>Energy Efficiency (kwH/miles)</td>
<td>Acceleration (0-30 mph)</td>
<td>Top Speed (miles/hour)</td>
<td>Source</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>------------------------</td>
<td>---------------------------</td>
<td>-------------------------------</td>
<td>------------------------</td>
<td>-----------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>BIO</td>
<td>0</td>
<td>11.35</td>
<td>N/A</td>
<td>3.6</td>
<td>100</td>
<td>(US Department of Energy, 2013)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>0</td>
<td>4.8</td>
<td>N/A</td>
<td>3.5</td>
<td>100</td>
<td>Author Assumption based on Honda Clarity performance parameters. (Honda Motors)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Vehicle Attribute Assumptions

Assumptions and initial values for other model wide parameters like the vehicle price, VMT per year etc are tabulated in Table 3 below:

<table>
<thead>
<tr>
<th>Model Variable</th>
<th>Value</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 VMT per year</td>
<td>8000 - 10,000</td>
<td>km/vehicle/year</td>
<td>(Gota, 2009, p. 14)</td>
</tr>
<tr>
<td>VMT Growth Rate</td>
<td>100 km/Year</td>
<td></td>
<td>(Gota, 2009, p. 14)</td>
</tr>
<tr>
<td>2000 India Median Household Income</td>
<td>Rs.28721</td>
<td>Rs</td>
<td>(Sonalde B. Desai, 2010, p. 12)</td>
</tr>
<tr>
<td>Model Variable</td>
<td>Value</td>
<td>Units</td>
<td>Source</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>--------------</td>
<td>----------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Effective Contact Rate Drivers</td>
<td>0.06</td>
<td>Dimensionless/year</td>
<td>(Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid-Electric, 2012, p. 156)</td>
</tr>
<tr>
<td>Effective Contact Rate Non Drivers</td>
<td>0</td>
<td>Dimensionless/year</td>
<td>(Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid-Electric, 2012, p. 156)</td>
</tr>
<tr>
<td>Initial Base Vehicle Cost</td>
<td>8,000</td>
<td>USD</td>
<td>Assumption based on price of popular model price</td>
</tr>
<tr>
<td>Model Variable</td>
<td>Value</td>
<td>Units</td>
<td>Source</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------</td>
<td>----------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Initial Experience Electric</td>
<td>1,000,000</td>
<td>vehicles</td>
<td>(Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid--Electric, 2012, p. 157)</td>
</tr>
<tr>
<td>Model Variable</td>
<td>Value</td>
<td>Units</td>
<td>Source</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------</td>
<td>-------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Learning Curve Strength</td>
<td>0.85</td>
<td>Dimensionless</td>
<td>(Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid--Electric, 2012, p. 157)</td>
</tr>
<tr>
<td>Initial CNG Storage Tank Cost</td>
<td>1980</td>
<td>USD</td>
<td>Assumed 18% of total vehicle cost based on the data in (Mukherjee, 2012)</td>
</tr>
<tr>
<td>Initial CNG Storage Experience</td>
<td>1500000</td>
<td>vehicles</td>
<td>(NGVJournal, 2013)</td>
</tr>
<tr>
<td>Initial R&amp;D CNG Storage Tank</td>
<td>10000000</td>
<td>USD</td>
<td>All technologies are assumed to start with 10 Million R&amp;D Budget</td>
</tr>
<tr>
<td>Initial H2 Storage Experience i</td>
<td>200</td>
<td>vehicles</td>
<td>(Ohnsman, 2008)</td>
</tr>
</tbody>
</table>

26
<table>
<thead>
<tr>
<th>Model Variable</th>
<th>Value</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial H2 Tank Cost</td>
<td>50,000</td>
<td>USD</td>
<td>Assumption to ensure that the effective MSRP reaches $120,000 as shown in (Ohnsman, 2008)</td>
</tr>
<tr>
<td>Initial R&amp;D H2 Storage Tank</td>
<td>10000000</td>
<td>USD</td>
<td>All technologies are assumed to start with 10 Million R&amp;D Budget</td>
</tr>
<tr>
<td>Initial H2 FCV Experience i</td>
<td>200</td>
<td>vehicles</td>
<td>(Ohnsman, 2008)</td>
</tr>
<tr>
<td>Initial H2 FCV Cost</td>
<td>50,000</td>
<td>USD</td>
<td>Assumption to ensure that the effective MSRP reaches $120,000 as shown in (Ohnsman, 2008)</td>
</tr>
<tr>
<td>Initial R&amp;D H2 FCV i</td>
<td>10000000</td>
<td>USD</td>
<td>All technologies are assumed to start with 10 Million R&amp;D Budget</td>
</tr>
<tr>
<td>Initial Gasoline Station</td>
<td></td>
<td></td>
<td>Assumption based on data that there were 23,000 stations in year 2003. (Ministry of Petroleum and Natural Gas, 2011)</td>
</tr>
<tr>
<td>Availability</td>
<td>20,000</td>
<td>Stations</td>
<td></td>
</tr>
<tr>
<td>Initial Gas Station Mix</td>
<td>60% Petrol pumps and 40% Diesel Pumps</td>
<td>Dimensionless</td>
<td>Author Assumptions based on interviews in India</td>
</tr>
</tbody>
</table>

Table 3: Vehicle Attribute Settings and Assumptions

Table 4 below provides the GHG factors used in the model for various fuels.
<table>
<thead>
<tr>
<th>Fuel</th>
<th>Green House Factor</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG Factor of Electricity</td>
<td>0.00064</td>
<td>tonnes CO2e/(kW*hour)</td>
<td>(U.S. Environmental Protection Agency, 2012)</td>
</tr>
<tr>
<td>GHG Factor for Gasoline</td>
<td>0.0087</td>
<td>tonne CO2e /GEG</td>
<td></td>
</tr>
<tr>
<td>GHG Factor of Diesel</td>
<td>0.0116</td>
<td>tonne CO2e /GEG</td>
<td></td>
</tr>
<tr>
<td>GHG Factor for Ethanol</td>
<td>0.0041</td>
<td>tonne CO2e /GEG</td>
<td></td>
</tr>
<tr>
<td>GHG Factor for CNG</td>
<td>0.0069</td>
<td>tonne CO2e /GEG</td>
<td></td>
</tr>
<tr>
<td>GHG Factor of H2</td>
<td>0.0150</td>
<td>tonne CO2e /GEG</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: GHG Emission Factors

Next I calibrate the S-Shaped Logistic Function used to simulate the vehicle installed base expansion. Figure 8 shows the comparison of the historical and simulated growth in the total installed base from year 2001 to 2011 (Ministry of Road Transport and Highways, 2009 -2010 & 2010-2011) while varying Population Growth Constant Alpha and Beta. The parameters Population Growth Constant Alpha (α) and Beta (β) are set to 12.6 and 0.3 respectively based on a sensitivity analysis.

Figure 8: Sensitivity Analysis of Historical and Simulated Growth in Total Installed base of Vehicles from 2000-2010 Source: (Ministry of Road Transport and Highways, 2009 -2010 & 2010-2011)
Once the model is calibrated, we use it to estimate the growth of installed base for various scenarios of GDP growth and population growth. Figure 9 and 10 shows the simulated growth in GDP and Population under various scenarios.

**Figure 9:** GDP Growth under Various Growth Scenarios

*Source:* (International Monetary Fund, 2013)

**Figure 10:** Population Growth Scenarios

*Source:* (United Nations, 2013)

The utility of each platform is computed using the platform utility function given by equation 24

\[ U_f = \frac{C_1 \times \text{Purchase Price}_f}{\ln(GDP \text{ Per Capita})} + C_2 \times \text{Operating Cost}_f + C_3 \times \text{Acceleration}_f + C_4 \times \] (24)
Top Speed\textsubscript{j} + C\textsubscript{5} \times Emissions\textsubscript{j} + C\textsubscript{6} \times Scope\textsubscript{j} + C\textsubscript{7} \times Refueling\ Cost\textsubscript{j}

Units: Dimensionless

Since there is no existing literature on the utility preference of Indian consumer for acceleration, top speed, emissions and scope, I retain the coefficients used by Keith (Keith, 2012). However, I use a different value for coefficients C\textsubscript{1} and C\textsubscript{2} that weights the sensitivity of the utility to the Acquisition price and Operating Cost, respectively. This is based on perceptions and interviews conducted with major automakers like Mahindra and Mahindra, GM and Tata Motors in India as well as a sensitivity analysis. A multivariate sensitivity analysis is performed by varying the values of C\textsubscript{1} (-0.9 to -0.7 in steps of 0.01) and C\textsubscript{2} (-0.3 to -0.225 in steps of 0.025) to mimic the uptake of diesel platform in year 2011. Figure 11 shows the contour plot of diesel installed base in 2011 for various values of C\textsubscript{1} and C\textsubscript{2}.

**Figure 11: Multivariate Sensitivity Analysis to Determine C\textsubscript{1} and C\textsubscript{2}**

Based on sensitivity analysis, setting C\textsubscript{1} and C\textsubscript{2} to -0.87 and -0.275 respectively causes the installed base of diesel vehicle to be approximately 3.75 million vehicles as was observed in India.

Next, I describe the calibration of parameters for refueling infrastructure availability and economics sections of the model. Based on interviews conducted in India with refueling Infrastructure owners, I assume the fixed cost of average station to be $200,000. I amortize it over the lifetime of the
infrastructure. It is also assumed that the station owners expect minimum target utilization of 10% on an average across the nation. These target profitability and utilization are parameterized to mimic the growth of gas station in India (Ministry of Petroleum and Natural Gas, 2011) as shown in Figure 12. Finally, I use historical retail prices of all fuels in constant 2012 USD for the years 2000 to 2011. The price of all crude based fuels ramp up at a constant rate from 2011 till the end of simulation as depicted in the Figure 13 below. The price of Biofuel and Hydrogen on the other hand are assumed to drop based on the learning in the technology of fuel separation.

Figure 12: Sensitivity of Available Infrastructure to Target Profitability and Utilization

Figure 13: Retail Price of Fuels
Based on these initial values, I construct a series of scenarios to explore the dominant factors influencing the alternative fuel vehicle adoption in India. In the simulation Gasoline and Diesel platforms are introduced in year 2000. We assume the introduction of all AFV platforms in year 2014.

I begin by estimating the market adoption of various platforms for under different market expansion scenarios. The greatest expansion in the automotive market occurs when the GDP per Capita growth of the economy is the most aggressive. This scenario occurs when the population growth is least aggressive and the GDP growth is most aggressive. The least expansion of the market on the other hand occurs when the population growth is most aggressive and the GDP growth least aggressive. Figure 14 below captures the growth in total installed base for the high growth, average growth and low growth scenarios. As can be seen the model estimates can vary over a huge range from 980 million in high growth scenario of 250 million in low growth scenario. We assume an average growth scenario of 550 million vehicles by year 2050 for scenario analysis.

**Figure 14: Estimation of Total Installed Base**

Next I construct scenarios where I explore various strategies for market introduction of AFVs in Indian market.
**Scenario 1: Base Case**

Here I establish the base case by introducing all the AFVs in the year 2014. The only incentive provided is the additional marketing spending of $50 Million per year for each AFV platform to generate awareness. Figure 15 and 16 show the model generated values for various parameters of interest. As can be seen in the graph of installed base, HEV and BIO are the first two AFV platforms to see any appreciable sales. However, by year 2028 rising Gasoline prices and increased GDP per capita cause the PHEV sales and sales to shoot past that of HEV. By the end of simulation in year 2050, we notice that the PHEV is the dominant AFV platform with an installed base of about 56 million Vehicles. It is important to note here that the public charging infrastructure (PLUG) is never established till the year 2050. PHEV charging is completely performed by home chargers. At this stage, we need to emphasize that the model assumes electricity is always available at the assumed prices with no reliability issues. However, in the recent past, the Indian grid has been plagued by poor reliability, and lack of capacity, leading to frequent blackouts and grid failures (Harris and Yardley, 2012). The supply side constrains in terms of availability and quality of electricity could adversely impact the adoption of PHEVs and BEVs leading to lower than predicted xEV penetration.

CNG and H2 platforms never take off due to absence of refueling infrastructure. However the dominant platforms are still Gasoline and Diesel with an estimated installed base of 236 million and 226 million vehicles respectively. The cumulative GHG Emissions estimated for this scenario is 22.6 Billion tonnes CO2 e.
Figure 15: Base Case Scenario
Scenario 2: National Electric Mobility Mission Plan Incentives

To promote the adoption of xEVs, the government of India unveiled a National Electric Mobility Mission Plan (NEMMP 2020). The plan aims to spur the growth of xEVs sales to about 1.7 million per year by 2020. The incentives proposed by the plan are as follows:
Table 5: NEMMP 2020 Demand Side Incentives

<table>
<thead>
<tr>
<th></th>
<th>Incentive per Vehicle ($/Vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEV</td>
<td>$1000</td>
</tr>
<tr>
<td>PHEV</td>
<td>$1500</td>
</tr>
<tr>
<td>BEV</td>
<td>$3000</td>
</tr>
</tbody>
</table>

In this scenario we implement the demand side incentives of NEMMP to the model. We also introduce exogenously 500 public charging stations per year for a period of 5 years with the goal of improving the percentage of public miles traveled by PHEV and BEVs. The cumulative spending of such an incentive is $428 million in vehicle subsidies.

Figure 17: Annual Sales of Alternative Fuel Vehicles

As can be seen in Figure 17, we notice a small uptake in BEV sales from year 2025 onwards. In the year 2020, the estimated combined installed base of HEV, PHEV and BEV is just 235,000 vehicles. Battery cost reduces from 12,800 $/vehicle to 7087 $/vehicle for PHEV platform because of learning in sales. The total installed base of alternative fuel vehicles is provided in the Figure 18. Figure 19 shows the evolution of charging station availability in India based on the incentives provided. Based on simulation results it is clear that a significant reduction in the battery price as well as a greater investment in marketing and awareness creation is necessary for the overall annual xEV sales to reach 1.7 million vehicles per year by year 2020. Figure 20 shows the GHG emissions of each platform. It is evident that the emissions due to the incentives do not see any appreciable decrease because of increased adoption of AFVs. This can be attributed to three reasons. Firstly India generates a bulk of its electricity from coal.
Hence the well to wheel emissions of BEVs and PHEVs are not significantly lower than conventional vehicles. Secondly, the Indian cars have a high average efficiency to cater to value conscious Indian car buyer. This reduces the emissions per mile generated by conventional vehicles. Thirdly, in the expanding market the dominant platforms are still Gasoline and Diesel with the PHEV penetration being less than 2%.

Figure 18: Total Installed base of AFV in India

Figure 19: Refueling Infrastructure Availability
Scenario 3: CNG Introduction Scenario

Here I construct a scenario where the CNG is introduced in the year 2010. We exogenously introduce 300 CNG stations per year to spur CNG adoption in India. Moreover, the initial installed base of CNG vehicles is assumed to be 100,000 vehicles. This installed base takes into account the already developed CNG fleet that is based on retrofit CNG fleets (taxis). The simulation results are presented in Figure 22 and 23. As can be seen, the CNG vehicles grow substantially under the incentives reaching a total installed base of 59 million vehicles. The dominant xEV platform still is PHEV, with a total installed base of 43 million vehicles in year 2050.
Figure 22: Scenario 3 - CNG Introduction

Figure 23: Scenario 3 - CNG Introduction
4. Conclusion and Future Research Opportunities

As can be seen in the results of the simulation, India has a rapidly expanding automotive market. It is extremely difficult to predict the actual vehicle installed base growth over long periods. Depending on various economic and demographic factors the total installed base of vehicles in India is estimated to be around 500 million vehicles. If there is a high GDP growth and low population growth, then the model estimates the vehicle installed base to be 578 million vehicles.

The expansion in installed base of vehicles has huge implications for global GHG emissions and energy consumption. The model estimates that the annual GHG emissions of all platforms in the business as usual scenario is estimated to be 1.52 billion tonnes CO2e per year by year 2050. The total cumulative emission is estimated to be 22.6 Billion tonnes CO2 e. It is imperative that India pursue strong policies to promote clean fuel efficient power trains. The model also reveals that increased penetration of EVs does not substantially reduce the GHG emissions. This is primarily because of two reasons. First, the primary source of electricity in India is Coal. Hence the well to wheel emission of electric vehicle is not substantially different from that of an efficient ICE. The second reason is because the overall penetration of xEVs is not substantial in comparison to the overall installed base of vehicles. It is therefore important that India transition to cleaner fuels to generate electricity, so as to ensure that the well to wheel GHG emissions reduces due to adoptions of xEVs.

The simulation predicts the PHEV to be the dominant AFV platform by 2050. In the business as usual case the total installed base of PHEV is estimated to be 30 million, with annual sales of 6 million vehicles per year. Providing demand side incentives as envisages in NEMMP improves the viability of BEVs by increasing the annual sales to 3.5 million vehicles per year by 2050. However, the simulation also reveals that the NEMMP incentives are inadequate to meet the demand generation targets of 2 million xEVs by 2020 as envisaged in the plan. It is important to note that the model assumes that there are no supply

40
side constraints for fuels. Relaxing this assumption and modeling the fuel supply side constraints endogenously could lead to lower than predicted xEV adoption.

Platform transitions in the automotive sector are extremely complex and challenging. Transitions require significant investment both by government and industry in terms of setting up of the refueling infrastructure, electricity availability, and grid reliability and consumer awareness creation to establish sustainable markets.

The model developed as a part of this work enables one to study numerous policy scenarios in terms of introduction of AFV platforms in the Indian market. However there are many opportunities to extend the model boundary and fidelity. Firstly, the weights of utility of various factors like acceleration, top speed and emissions to Indian consumer is assumed to be same as that of US consumers as detailed in Keith model (Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid-Electric, 2012) because of absence of empirical studies. Empirical conjoint analysis studies of car buyer preferences could provide better understanding of the dynamics of vehicle adoption in India. Secondly, Indian automotive market is dominated by two wheelers. This model can be easily extended to study the electric two wheeler adoption in the Indian scenario. Thirdly, the model represents each platform as a single entity. Incorporating dynamics of competition between multiple business entities with portfolio of platforms would make the evolution of each platform more realistic.

As mentioned before, the model assumes that the VKT increases at a constant rate, irrespective of the economic conditions. The model fidelity can be further improved by making the VKT a function of economy. Finally, the model assumes an average customer with a homogenous utility and buying capacity. Separating the consumers to different segments with different utility weighting factors, might show different dynamics of adoption for AFV.
References


Gota, B. F. (2009). Emissions from India’s Intercity and Intracity Road Transport. CAI-Asia Center, 10.


Appendix- A : Model Code

Market Share Expansion

The structural additions performed to Keith model (Keith, 2012) are documented below.

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>i GAS, HEV, PHEV, BEV, CNG, Diesel, H2, Bio</td>
</tr>
<tr>
<td>TechnologyTo</td>
<td>j GAS, HEV, PHEV, BEV, CNG, Diesel, H2, Bio</td>
</tr>
<tr>
<td>Fuels</td>
<td>r GASOLINEFUEL, DIESELFUEL, BIOFUEL, CNGFUEL, H2FUEL, ELECTRICITY</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>f GASPUMP, PLUG, CNGPUMP, H2PUMP</td>
</tr>
<tr>
<td>Gaspumpmix</td>
<td>g GASOLINEPUMP, DIESELPUMP, BIOPUMP</td>
</tr>
</tbody>
</table>

Table 6: Model Subscripts

Desired Installed Base $i[\text{TechnologyTo}] = \text{Desired Vehicle Stock} \times \text{Projected Market Share } j[\text{TechnologyTo}]$

Units: vehicles

_Desired installed base is a product of total desired vehicle stock and projected market share of platform j in a given market._

Desired Stock of Vehicles per Thousand People = Vehicle Saturation Percentage * Initial Car Population for Thousand People * EXP(Population Growth Cost * GDP per Capita by Total Cost of Ownership-del) / (Vehicle Saturation Percentage + (EXP(Population Growth Cost * GDP per Capita by Total Cost of Ownership-del) - 1))

Units: vehicles/person

_S shaped Logistic function described in equation 1 characterizes the growth of total installed base as a function of GDP per capita and the total cost of ownership in a country._

Population Growth Cost = 12.6

Units: person/vehicles

Del = 0.3

Units: Dimensionless

Vehicle Saturation Percentage = 68.3

Units: Dimensionless
Logistic Function Growth Constants are used to characterize the shape of the S curve. Vehicle saturation level is assumed to be 683 cars per thousand people.

Desired Vehicle Stock = Population*Desired Stock of Vehicles per Thousand People/1000
Units: vehicles

Desired vehicle stock is calculated by multiplying the population over 1000 with the desired vehicle stock per thousand persons

GDP= INTEG (GDP Growth Rate,1.81492e+012)
Units:$

GDP Growth Rate= IF THEN ELSE(GDP SW= LOW, GDP PPP Low Growth Rate TF(Time), IF THEN ELSE(GDP SW = MED, GDP PPP Medium Growth Rate TF (Time) , GDP PPP High Growth Rate TF(Time) ) )*GDP/100
Units:$/year

GDP growth rate is calculated a stock that grows according to a tabulated historical values from year 2000-2011. It grows at a predefined constant rate from 2011 till the end of simulation. IF THEN ELSE is used to select different growth rates for sensitivity analysis.

Population =IF THEN ELSE(Pop SW =LOW, Population Low TF(Time) , IF THEN ELSE(Pop SW=MED, Population Med TF (Time) , Population High TF(Time)) )
Units: person

Population is a table function based on UN data and statistics.

GDP Per Capita= ZIDZ(GDP, Population )
Units: $/person

GDP per capita is simply the total GDP by the total population.

GDP per Capita by Total Cost of Ownership= GDP Per Capita/Total Cost of Ownership
Units: vehicles/person

GDP per Capita by Total Cost of Ownership determines the vehicle buying capacity in the population.

Effective Vehicle Price j[TechnologyTo]= MSRP j[TechnologyTo]-Vehicle Incentives j[TechnologyTo]+EV Home Charger Cost j[TechnologyTo]
Units: $/vehicles

Effective price is the total cost of vehicle and supporting infrastructure like home charger minus the incentives that may be provided to promote a platform.
Expected Growth in Market Share $j[TechnologyTo]=SMOOTH(Indicated Market Share Growth $j[TechnologyTo], Time to Perceive Market Share Growth $i)$
Units: Dimensionless/year
Time to Perceive Market Share Growth $i = 1$
Units: year
"Forecast Horizon - Market Share" $= 1$
Units: year
Indicated Market Share Growth $j[TechnologyTo]=TREND(Recent Market Share of Installed Base $i[TechnologyTo], Historic Time Horizon of Market Share Growth $i, Initial market Share Growth Rate $i)$
Units: Dimensionless/year
Historic Time Horizon of Market Share Growth $i = 1$
Units: year
Initial market Share Growth Rate $i = 0$
Units: Dimensionless/year
Market Share Perception Time $= 1$
Units: year
Recent Market Share of Installed Base $i[Technology]=SMOOTH(Market Share of Installed Base $i[Technology], Market Share Perception Time )$
Units: Dimensionless
Projected Market Share $j[TechnologyTo]=(Recent Market Share of Installed Base $i[TechnologyTo])*(1+("Forecast Horizon - Market Share" * Expected Growth in Market Share $j[TechnologyTo])))$
Units: Dimensionless
Target Stock Adjustment Delay $= 1$
Units: year

The share of vehicles in a market is perceived after a delay by the population. Hence projected market share is used to determine the share of desired vehicle mix. The delay in perception of market share changes is modeled above using SMOOTH function.

Market Share of Installed Base $i[Technology]=\frac{Installed Base i[Technology]}{SUM(Installed Base i[Technology!])}$
Units: Dimensionless

NPV of Operating Cost Technology $=\text{NPV}(\text{Operating Cost per Year Technology}, df , \text{Init Value Technology} , 1)$
Units: $/vehicles$
df $= 0.1$
Units: Dimensionless/year
Total Cost of Ownership $=\text{Effective Vehicle Price Technology GAS} + \text{NPV of Operating Cost GAS}$
Units: $/vehicles$
Total cost of ownership is the sum of acquisition price and NPV of the operating cost. We have assumed a 10% annual discount factor over the lifetime of the vehicle.

Platform Demand Adjustment due to Market Expansion $j[\text{Technology}] = ZIDZ(\text{Desired Installed Base }i[\text{Technology}] - \text{Installed Base }i[\text{Technology}], \text{Target Stock Adjustment Delay})$

Units: vehicles/year

Platform demand adjustment acts as a balancing feedback loop correcting the error in desired vehicle stock of a given platform to the observed installed base.

**Fleet Turnover – (Ageing Supply Chain)**

Initial Light Vehicle Market Size $j[\text{GAS}] = 6e+006$
Initial Light Vehicle Market Size $j[\text{Diesel}] = 500000$
Initial Light Vehicle Market Size $j[\text{HEV}] = 0$
Initial Light Vehicle Market Size $j[\text{CNG}] = 100000$
Initial Light Vehicle Market Size $j[\text{PHEV}] = 0$
Initial Light Vehicle Market Size $j[\text{BEV}] = 0$
Initial Light Vehicle Market Size $j[\text{Bio}] = 0$
Initial Light Vehicle Market Size $j[\text{H2}] = 0$

Units: vehicles

Vehicle fleet size is initialized at the beginning of simulation.

Vehicle Lifetime = 15
Units: year
The vehicle lifetime is assumed to be 15 years.

"(Vehicle Discards $i$) New Vehicle Purchasers by Current Platform $i[\text{Technology}] = \text{Vehicles 0 to 4 Retirements } i[\text{Technology}]+\text{Vehicles 5 to 8 Retirements }i[\text{Technology}]+\text{Vehicles 9 to 12 Retirements }i[\text{Technology}]+\text{Vehicles 13 plus Retirements }i[\text{Technology}])$

Units: vehicles/year

Vehicle discards is sum of discards or retirements of vehicles from each cohort of vehicles in the market.

"Initial Installed Base - Used Vehicles $i[\text{Technology}] = "\text{Initial Installed Base - Vehicles 5 to 8 years }i[\text{Technology}]+\"\text{Initial Installed Base - Vehicles 9 to 12 years }i[\text{Technology}]+\"\text{Initial Installed Base - Vehicles 13 plus years }i[\text{Technology}]

Units: vehicles
"Initial Installed Base - Vehicles 0 to 4 years i"[Technology] = \( \frac{\text{Aging Time Lambda}}{\text{Vehicle Lifetime}} \) \* Initial Light Vehicle Market Size j[Technology]
Units: vehicles

"Initial Installed Base - Vehicles 13 plus years i"[Technology] = \( \frac{(\text{Vehicle Lifetime}-3\times\text{Aging Time Lambda})}{\text{Vehicle Lifetime}} \) \* Initial Light Vehicle Market Size j[Technology]
Units: vehicles

"Initial Installed Base - Vehicles 5 to 8 years i"[Technology] = \( \frac{\text{Aging Time Lambda}}{\text{Vehicle Lifetime}} \) \* Initial Light Vehicle Market Size j[Technology]
Units: vehicles

"Initial Installed Base - Vehicles 9 to 12 years i"[Technology] = \( \frac{\text{Aging Time Lambda}}{\text{Vehicle Lifetime}} \) \* Initial Light Vehicle Market Size j[Technology]
Units: vehicles

Initial Installed Base i[Technology] = "Initial Installed Base - Vehicles 0 to 4 years i"[Technology] + "Initial Installed Base - Used Vehicles i" [Technology]
Units: vehicles

Aging Time Lambda = 4
Units: year

The entire stock of vehicles is divided into cohorts of vehicles which are in the group of 0-4 years, 5-8 years, 9-12 years and 13-15 years respectively. Each cohort has a specific discard rate. The stock of vehicles 0-4 feeds into stock of vehicles aged 5-8 at a constant rate and so on.

Installed Base i[Technology] = Vehicles 0 to 4 years i[Technology] + Used Vehicles i[Technology]
Units: vehicles

Installed base is the sum of new vehicles and used vehicles in a market.

Order Fulfillment j[TechnologyTo] = IF THEN ELSE ( SW Capacity Constraints On=1 , Deliveries j[TechnologyTo] , Platform Demand j [TechnologyTo] )
Units: vehicles/year

Platform Demand Adjustment due to Market Expansion j[Technology] = MAX(0,ZIDZ( Desired Installed Base i[Technology]-Installed Base i[Technology] , Target Stock Adjustment Delay ))
Units: vehicles/year

Platform Demand j[TechnologyTo] = SUM("(Vehicle Discards i) New Vehicle Purchasers by Current Platform i"[Technology]!*Share ij[Technology!,TechnologyTo]) + Platform Demand Adjustment due to Market Expansion j[TechnologyTo]
Units: vehicles/year

Vehicle Sales i[Technology] = Order Fulfillment j[Technology]
Units: vehicles/year
New vehicle sales is driven by the platform demand which is in turn drives the order fulfillment. If capacity constrain exists then the order fulfillment is dependent on production capacity. However if the capacity constrain is off then the order fulfillment tracks the platform demand. New vehicle sales add to the stock of vehicles in the market. Vehicle discards removes vehicles from the market.

Total Installed Base = SUM(Installed Base i[Technology])
Units: vehicles

Total installed base is simply the sum of installed base of vehicles in all platforms.

Used Vehicles i[Technology] = Vehicles 5 to 8 years i[Technology]+Vehicles 9 to 12 years i[Technology]+"Vehicles 13+ years i"[Technology]
Units: vehicles

Vehicle Aging 3 i[Technology] = Vehicles 9 to 12 years i[Technology]/Aging Time Lambda
Units: vehicles/year

Vehicle Aging 2 i[Technology] = Vehicles 5 to 8 years i[Technology]/Aging Time Lambda
Units: vehicles/year

Vehicle Aging i[Technology] = Vehicles 0 to 4 years i[Technology]/Aging Time Lambda
Units: vehicles/year

Vehicles 0 to 4 Retirements i 0[Technology]= NV Discard Fr*Vehicles 0 to 4 years i[Technology]
Units: vehicles/year
NV Discard Fr= 0.001
Units: dmnl/year

Vehicles 0 to 4 years i[Technology]= INTEG (Vehicle Sales i[Technology]-Vehicles 0 to 4 Retirements i 0[Technology]-Vehicle Aging i[Technology],"Initial Installed Base - Vehicles 0 to 4 years i"[Technology])
Units: vehicles

Stock of vehicles in 0-4 cohort increases with vehicle sales i and vehicle aging i. NV Discard Fr is assumed to be 0.001 per year.

Vehicles 5 to 8 Retirements i[Technology]= Vehicles 5 to 8 years i[Technology]*Vehicles 5 to 8 Discard Fraction
Units: vehicles/year
Vehicles 5 to 8 Discard Fraction= 0.01
Units: dmnl/year
Vehicles 5 to 8 years i[Technology] = INTEG (Vehicle Aging i[Technology] - Vehicle Aging 2 i[Technology] - Vehicles 5 to 8 Retirements i [Technology], "Initial Installed Base - Vehicles 5 to 8 years i"[Technology])
Units: vehicles

Stock of vehicles in 5-8 cohort increases with Vehicle Aging i and decreases with Vehicle Aging 2 i. Vehicles 5 to 8 Discard Fraction is assumed to be 0.01 per year

Vehicles 9 to 12 Retirements i[Technology] = Vehicles 9 to 12 years i[Technology] * Vehicles 9 to 12 Discard Fraction
Units: vehicles/year
Vehicles 9 to 12 Discard Fraction = 0.1
Units: dmnl/year

Vehicles 9 to 12 years i[Technology] = INTEG (Vehicle Aging 2 i[Technology] - Vehicle Aging 3 i[Technology] - Vehicles 9 to 12 Retirements i [Technology], "Initial Installed Base - Vehicles 9 to 12 years i"[Technology])
Units: vehicles

Stock of vehicles in 9-12 cohort increases with Vehicle Aging 2 i and decreases with Vehicle Aging 3 i. Vehicles 9 to 12 Discard Fraction is assumed to be 0.1 per year

Vehicles 13 plus Retirements i[Technology] = "Vehicles 13+ years i"[Technology] * Vehicles Retirement Fraction
Units: vehicles/year
Vehicles Retirement Fraction = 0.3
Units: dmnl/year

"Vehicles 13+ years i"[Technology] = INTEG (Vehicle Aging 3 i[Technology] - Vehicles 13 plus Retirements i[Technology], "Initial Installed Base - Vehicles 13 plus years i"[Technology])
Units: vehicles

Stock of vehicles in 13+ cohort increases with Vehicle Aging 3 i and decreases with Vehicles 13 plus Retirements i. Vehicles Retirement Fraction is assumed to be 0.3 per year

Vehicle Choice Modeling

"Ln(GDP Per Capita)" = LN(GDP Per Capita/Ln Units Correction)
Units: Dimensionless
Purchase Price Weight = -1.17
Units: Dimensionless/\$/vehicles

\[ U_1_{[TechnologyTo]} = \left( \frac{\text{Effective Vehicle Price}_{[TechnologyTo]}}{1000} / \ln(\text{GDP Per Capita}) \right) \times \text{Purchase Price Weight} \]
Units: Dimensionless

*Lower acquisition cost implies higher utility.*

Vehicle Operating Cost \( i \) = \( Z_{IDZ} \times \text{Retail Fuel Price}_{r,FE} \) by Platform by Fuel \( ir \)
\( \forall \, i \in \{ \text{GAS, DIESEL, HEV, BEV, CNG, H2, BIO} \} \)
Units: \$/miles

*Operating cost of a platform is the retail price of fuel divided by the fuel efficiency of the platform to that fuel.*

Vehicle Operating Cost \( i_{[PHEV]} \) = "% All Electric Miles by Platform \( j \)\[PHEV]\) \( Z_{IDZ} \times \text{Retail Fuel Price}_{r[\text{ELECTRICITY}], \text{FE} \text{by Platform by Fuel} \, ir[\text{PHEV, ELECTRICITY}] + (1-"% All Electric Miles by Platform \( j \)\[PHEV]\) \( Z_{IDZ} \times \text{Retail Fuel Price}_{r[\text{GASOLINEFUEL}], \text{FE} \text{by Platform by Fuel} \, ir[\text{PHEV, GASOLINEFUEL}] \)
Units: \$/miles

*Operating cost of a platform is the retail price of fuel divided by the fuel efficiency of the platform to that fuel. For PHEV the total operating cost is the operating cost of the electric miles + operating cost of the gasoline miles.*

Vehicle Operating Cost in Cents \( i_{[Technology]} \) = Vehicle Operating Cost \( i_{[Technology]} \) \times \text{Cents per Dollar}
Units: cents/miles

Operating Cost Weight = -0.275
Units: Dimensionless/(cents/miles)

\[ U_2_{[TechnologyTo]} = \text{Operating Cost Weight} \times \text{Vehicle Operating Cost in Cents}_{i_{[TechnologyTo]}} \]
Units: Dimensionless

*Lower operating cost implies higher utility.*

Acceleration Weight = -0.149
Units: Dimensionless/seconds

\[ U_3_{[TechnologyTo]} = \text{Acceleration Weight} \times \text{Acceleration by Platform}_{j_{[TechnologyTo]}} \]
Units: Dimensionless
0-30 acceleration is measured in seconds. A lower time constant implies higher acceleration and hence higher utility.

**Top Speed Weight**  
Top Speed Weight = 0.272  
Units: Dimensionless/(miles/hour)  
U4 \( j[\text{TechnologyTo}] = \) Top Speed Weight * Top Speed by Platform \( j[\text{TechnologyTo}] \)/100  
Units: Dimensionless

*Higher top speed implies higher vehicle utility.*

**Emissions Fr Weight**  
Emissions Fr \( j[\text{Technology}] = \) Emissions per Mile \( j[\text{Technology}] \)/Emissions per Mile \( j[\text{GAS}] \)  
Units: Dimensionless  
Emissions Fr Weight = -0.149  
Units: Dimensionless  
U6 \( j[\text{TechnologyTo}] = \) Emissions Fr Weight * Emissions Fr \( j[\text{TechnologyTo}] \)  
Units: Dimensionless

*Lower emissions implies higher vehicle utility.*

**Annual Refueling Cost**  
Annual Refueling Cost \( i[\text{Technology}] = \) SUM(Annual Refueling Cost \( i[\text{Technology,Infrastructure!}] \))  
Units: \$/year/vehicles  
Fuel Search Cost \( j[\text{TechnologyTo}] = \) ZIDZ(Annual Refueling Cost \( i[\text{TechnologyTo}] \)*Cents per Dollar, VMT per Year \( i[\text{TechnologyTo}] \)*VMT SW \( i[\text{TechnologyTo}] \) )  
Units: cents/miles  
U7 \( j[\text{TechnologyTo}] = \) Fuel Search Cost \( j[\text{TechnologyTo}] \)*Operating Cost Weight  
Units: Dimensionless

*Lower refueling cost implies higher vehicle utility.*

**Reference Deliveries**  
Reference Deliveries = 2e+007  
Units: vehicles  
Delivery Fraction of Scope Threshold \( j[\text{Technology}] = \) ZIDZ(Cumulative Order Fulfillment \( j[\text{Technology}] \), Reference Deliveries)  
Units: Dimensionless  
Scope \( j[\text{Technology}] = \) IF THEN ELSE( Technology=GAS, 1, \( 1/(1+\exp((-\text{Sensitivity}*\text{Delivery Fraction of Scope Threshold } j[\text{Technology}])+(\text{Sensitivity}/2)))) \)  
Units: Dimensionless  
Scope Weight = -0.5  
Units: Dimensionless

*Scope is a proportional to the cumulative orders fulfilled.*

U8 \( j[\text{Technology}] = \) IF THEN ELSE( Technology=GAS, 0, \( (-\text{Scope Weight}/(1+\exp((-\text{Sensitivity}*\text{Delivery Fraction of Scope Threshold } j[\text{Technology}])+(\text{Sensitivity}/2))))+\text{Scope Weight} \) )
Utility \( j[\text{TechnologyTo}] \) = \( U_1 j[\text{TechnologyTo}] + U_2 j[\text{TechnologyTo}] + U_3 j[\text{TechnologyTo}] + U_4 j[\text{TechnologyTo}] + U_6 j[\text{TechnologyTo}] + U_7 j[\text{TechnologyTo}] + U_8 j[\text{TechnologyTo}] \)

Units: Dimensionless

The sum of utility of all the parameters determines the total utility of the platform.

Affinity \( ij[\text{Technology}, \text{TechnologyTo}] \) = Familiarity \( ij[\text{Technology}, \text{TechnologyTo}] \) * EXP Utility \( j[\text{TechnologyTo}] \)

Units: Dimensionless

Affinity of a platform is the product of familiarity of the platform and the exponent of utility.

EXP Utility \( j[\text{TechnologyTo}] \) = IF THEN ELSE((Platform Introduction Date \( j[\text{TechnologyTo}] \) > Time)), 0, IF THEN ELSE((TechnologyTo=GAS:OR:TechnologyTo=Diesel:OR:TechnologyTo=PHEV:OR:TechnologyTo=BEV), EXP(Utility \( j[\text{TechnologyTo}] \) / NMNL Lambda), EXP(Utility \( j[\text{TechnologyTo}] \)))

Units: Dimensionless

NMNL Lambda = 0.8
Units: Dimensionless

For the platforms that are in the nest we divide the utility by the nesting lambda as per the nested multinomial logit formulation. The NMNL lambda is assumed to be 0.8

Familiarity \( ij[\text{Technology}, \text{TechnologyTo}] \) = Average Familiarity \( ij[\text{Technology}, \text{TechnologyTo}] \)
Units: Dimensionless

The familiarity accumulation is same as that presented in David Keith’s model (Keith, Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid–Electric, 2012)

Logit Denominator[Technology]=
IF THEN ELSE(Inclusive Value of Liq Fuel \( i[\text{Technology}] \) = 0, 0, EXP(Inclusive Value of Liq Fuel \( i[\text{Technology}] \) * NMNL Lambda) ) +
IF THEN ELSE(Inclusive Value of Plug \( i[\text{Technology}] \) = 0, 0, EXP(Inclusive Value of Plug \( i[\text{Technology}] \) * NMNL Lambda) ) +
IF THEN ELSE(Affinity \( ij[\text{Technology}, \text{HEV}] \) = 0, 0, EXP(LN(Affinity \( ij[\text{Technology}, \text{HEV}] \) )) +
IF THEN ELSE(Affinity \( ij[\text{Technology}, \text{Bio}] \) = 0, 0, EXP(LN(Affinity \( ij[\text{Technology}, \text{Bio}] \) )) +
IF THEN ELSE(Affinity \( ij[\text{Technology}, \text{CNG}] \) = 0, 0, EXP(LN(Affinity \( ij[\text{Technology}, \text{CNG}] \) )) +
IF THEN ELSE(Affinity \( ij[\text{Technology}, \text{H2}] \) = 0, 0, EXP(LN(Affinity \( ij[\text{Technology}, \text{H2}] \) )) )
Denominator of Nested Multinomial Logit function

Inclusive Value of Liq Fuel \( i[\text{Technology}] \) = IF THEN ELSE( (Affinity \( ij[\text{Technology},\text{GAS}] \) + Affinity \( ij[\text{Technology},\text{Diesel}] \)) = 0, 0, \( \ln(\text{Affinity } ij[\text{Technology},\text{GAS}] + \text{Affinity } ij[\text{Technology},\text{Diesel}]) \) )
Units: Dimensionless

Inclusive Value of Plug \( i[\text{Technology}] \) = IF THEN ELSE(Affinity \( ij[\text{Technology},\text{PH EV}] \) + Affinity \( ij[\text{Technology},\text{BEV}] \)) = 0, 0, \( \ln(\text{Affinity } ij[\text{Technology},\text{PH EV}] + \text{Affinity } ij[\text{Technology},\text{BEV}]) \) )
Units: Dimensionless

Inclusive value of plug and ICE nest is the logarithm of sum of utilities.

Liquid Fuel Nest Share \( i[\text{Technology}] \) = \( \text{ZIDZ}(\exp(\text{Inclusive Value of Liq Fuel } i[\text{Technology}] \cdot \text{NMNL Lambda}), \text{Logit Denominator}[\text{Technology}]) \)
Units: Dimensionless

Plug In Share \( i[\text{Technology}] \) = IF THEN ELSE(Inclusive Value of Plug \( i[\text{Technology}] \)) = 0, 0, \( \text{ZIDZ}(\exp(\text{Inclusive Value of Plug } i[\text{Technology}] \cdot \text{NMNL Lambda}), \text{Logit Denominator}[\text{Technology}]) \)
Units: Dimensionless

Bio Share \( i[\text{Technology}] \) = IF THEN ELSE(Affinity \( ij[\text{Technology},\text{Bio}] \)) = 0, 0, \( \text{ZIDZ}(\exp(\ln(\text{Affinity } ij[\text{Technology},\text{Bio}]) ), \text{Logit Denominator}[\text{Technology}]) \)
Units: Dimensionless

CNG Share \( i[\text{Technology}] \) = IF THEN ELSE(Affinity \( ij[\text{Technology},\text{CNG}] \)) = 0, 0, \( \text{ZIDZ}(\exp(\ln(\text{Affinity } ij[\text{Technology},\text{CNG}]) ), \text{Logit Denominator}[\text{Technology}]) \)
Units: Dimensionless

H2 Share \( i[\text{Technology}] \) = IF THEN ELSE(Affinity \( ij[\text{Technology},\text{H2}] \)) = 0, 0, \( \text{ZIDZ}(\exp(\ln(\text{Affinity } ij[\text{Technology},\text{H2}]) ), \text{Logit Denominator}[\text{Technology}]) \)
Units: Dimensionless

HEV Share \( i[\text{Technology}] \) = IF THEN ELSE(Affinity \( ij[\text{Technology},\text{HEV}] \)) = 0, 0, \( \text{ZIDZ}(\exp(\ln(\text{Affinity } ij[\text{Technology},\text{HEV}]) ), \text{Logit Denominator}[\text{Technology}]) \)
Units: Dimensionless

Share \( ij[\text{Technology},\text{GAS}] \) = Liquid Fuel Nest Share \( i[\text{Technology}] \) \( \times \text{ZIDZ}(\text{Affinity } ij[\text{Technology},\text{GAS}], (\text{Affinity } ij[\text{Technology},\text{GAS}] + \text{Affinity } ij[\text{Technology},\text{Diesel}])) \)

Share \( ij[\text{Technology},\text{HEV}] \) = HEV Share \( i[\text{Technology}] \)
Share $ij[Technology,PHEV] = \text{Plug In Share } i[Technology] \times \text{ZIDZ (Affinity } ij[Technology,PHEV], (\text{Affinity } ij[Technology,PHEV] + \text{Affinity } ij[Technology,BEV]))$

Share $ij[Technology, BEV] = \text{Plug In Share } i[Technology] \times \text{ZIDZ (Affinity } ij[Technology, BEV], (\text{Affinity } ij[Technology, PHEV] + \text{Affinity } ij[Technology, BEV]))$

Share $ij[Technology, Diesel] = \text{Liquid Fuel Nest Share } i[Technology] \times \text{ZIDZ (Affinity } ij[Technology, Diesel], (\text{Affinity } ij[Technology, Gas] + \text{Affinity } ij[Technology, Diesel]))$

Share $ij[Technology, Bio] = \text{Bio Share } i[Technology]$

Share $ij[Technology, H2] = \text{H2 Share } i[Technology]$

Share $ij[Technology, CNG] = \text{CNG Share } i[Technology]$

Units: Dimensionless

*Share of each technology platform is determined by NMNL function as described in chapter 2.*

**Infrastructure Availability and Economics**

Infrastructure Life $f[Infrastructure] = 20$

Units: year

*Infrastructure life is assumed to be 20 years.*

Initial Infrastructure Availability $f[Infrastructure] = 20000, 0, 0, 0$

Units: stations

Initial Infrastructure in Construction $f[Infrastructure] = 2000, 0, 0, 0$

Units: stations

*Initially we assume 20,000 gas stations and 2000 gas stations in construction.*

Available Infrastructure $f[Infrastructure] = \text{INTEGRAL (Infrastructure Acquisition Rate } f[Infrastructure] - \text{Infrastructure Exits } f[Infrastructure] + \text{Exogenous Infrastructure } f[Infrastructure], \text{ Initial Infrastructure Availability } f[Infrastructure])$

Units: stations

$\text{Available Infrastructure } f = \text{Initial Infrastructure Availability } f$

$+ \int (\text{Infrastructure Acquisition Rate } f + \text{Exogenous Infrastructure } f - \text{Infrastructure Exits } f)$

Infrastructure Acquisition Rate $f[Infrastructure] = \text{ZIDZ (Infrastructure in Construction } f[Infrastructure], \text{ Time to Install Infrastructure } f[Infrastructure])$

Units: stations/year
Infrastructure Acquisition Rate \( f = \frac{\text{Infrastructure in Construction } f}{\text{Time to Install Infrastructure } f} \)

Time to Install Infrastructure \( f[\text{Infrastructure}] = 2,2,2,2 \)
Units: year

*Time to Install infrastructure is 2 years.*

Infrastructure Exits \( f[\text{Infrastructure}] = \text{ZIDZ}(\text{Available Infrastructure } f[\text{Infrastructure}], \text{Infrastructure Life } f[\text{Infrastructure}]) \)
Units: stations/year

\[ \text{Infrastructure Exits } f = \frac{\text{Available Infrastructure } f}{\text{Infrastructure Life } f} \]

Infrastructure in Construction \( f[\text{Infrastructure}] = \text{INTEG} \left( \text{Infrastructure Order Rate } f[\text{Infrastructure}] - \text{Infrastructure Acquisition Rate } f[\text{Infrastructure}], \text{Initial Infrastructure in Construction } f[\text{Infrastructure}] \right) \)
Units: stations

\[ \text{Infrastructure in Construction } f = \text{Initial Infrastructure in Construction } f \]
\[ + \int \text{Infrastructure Order Rate } f - \text{Infrastructure Acquisition Rate} \]

Infrastructure Loss Rate \( f[\text{Infrastructure}] = \text{Infrastructure Exits } f[\text{Infrastructure}] \)
Units: stations/year

*Infrastructure Loss Rate } f \text{ is the total number of station exits in a given year.}

Infrastructure Order Rate \( f[\text{Infrastructure}] = \text{MAX}(0, \text{Desired Infrastructure Acquisition Rate } f[\text{Infrastructure}] - \text{Infrastructure Supply Line Adjustment } f[\text{Infrastructure}]) \)
Units: stations/year

*The infrastructure order rate is Desired Infrastructure Acquisition Rate } f \text{ minus the Infrastructure Supply Line Adjustment } f. 

Infrastructure Stock Level Adjustment \( f[\text{Infrastructure}] = \text{ZIDZ}(\text{Available Infrastructure } f[\text{Infrastructure}] \times \text{Effect of Utilization on Desired Infrastructure } f[\text{Infrastructure}] \times \text{Effect of Profitability on Desired Infrastructure } f[\text{Infrastructure}] - \text{Available Infrastructure } f[\text{Infrastructure}], \text{Time to Install Infrastructure } f[\text{Infrastructure}]) \)
Units: stations/year

*Available infrastructure is adjusted based on projected utility and profitability of a platform.*
Infrastructure Supply Line Adjustment $f_{\text{Infrastructure}} = \frac{\text{Infrastructure in Construction}}{\text{Supply Line Adjustment Time}}$
Units: stations/year

*Infrastructure Supply Line Adjustment is equal to Infrastructure in Construction divided by Supply Line Adjustment Time.*

Desired Infrastructure Acquisition Rate $f_{\text{Infrastructure}} = \text{Infrastructure Loss Rate} f_{\text{Infrastructure}} + \text{Infrastructure Stock Level Adjustment} f_{\text{Infrastructure}}$
Units: stations/year

*Equation 21 in thesis represents the Desired Infrastructure Acquisition Rate.*

Ratio of Projected Profit to Target Profitability $f_{\text{Infrastructure}} = \text{XIDZ( Projected Station Profits } f_{\text{Infrastructure}}, \text{ Target Profitability[Infrastructure]),1 )}$
Units: Dimensionless

*Ratio of projected to target profits determine the effect of profits on infrastructure availability. Greater profits imply greater incentive to build infrastructure.*

Ratio of Projected Utilization and Target Utilization $f_{\text{Infrastructure}} = \text{XIDZ(Projected Infrastructure Utilization } f_{\text{Infrastructure}}, \text{ Target Utilization },1)$
Units: Dimensionless

*Ratio of projected to target utilization determines the effect of utilization on infrastructure availability. Greater utilization imply greater incentive to build infrastructure.*

Infrastructure Utilization $f_{\text{Infrastructure}} = \text{MIN}(0.9999, \text{IF THEN ELSE}( \text{Demand for Infrastructure } f_{\text{Infrastructure}}>0, \text{XIDZ( Demand for Infrastructure } f_{\text{Infrastructure}}, \text{ Available Infrastructure } f_{\text{Infrastructure}}, 0 ), \text{ZIDZ(Demand for Infrastructure } f_{\text{Infrastructure}}, \text{Available Infrastructure } f_{\text{Infrastructure}}) ))$
Units: Dimensionless

*Infrastructure Utilization is Demand for Infrastructure divided by Available Infrastructure.

Historic Time Horizon for Infrastructure Growth $= 1$
Units: year

Indicated Profit Growth $f_{\text{Infrastructure}} = \text{TREND(Recent Station Profits } f_{\text{Infrastructure}}, \text{ Historic Time Horizon for Infrastructure Growth }, \text{ initial Profit Growth Rate } f_{\text{Infrastructure}})$
Units: Dimensionless/year
Indicated Utilization Growth Rate $f[\text{Infrastructure}] = \text{TREND}(\text{Recent Utilization } f[\text{Infrastructure}], \text{Historic Time Horizon for Infrastructure Growth}, \text{Initial Utilization Growth Rate})$

Units: Dimensionless/year

Expected Growth in Utilization $f[\text{Infrastructure}] = \text{SMOOTH}(\text{Indicated Utilization Growth Rate } f[\text{Infrastructure}], \text{Time to Perceive Infrastructure Growth})$

Units: Dimensionless/year

Projected Infrastructure Utilization $f[\text{Infrastructure}] = (\text{Recent Utilization } f[\text{Infrastructure}] \times (1 + (\text{Forecast Horizon - Infrastructure} \times \text{Expected Growth in Utilization } f[\text{Infrastructure}])))$

Units: Dimensionless

Projected utilization forecast.

Initial Profit Growth Rate $f[\text{Infrastructure}] = 0$

Units: Dimensionless/year

Initial Utilization Growth Rate $= 0$

Units: Dimensionless/year

Expected growth in Profits $f[\text{Infrastructure}] = \text{SMOOTH}(\text{Indicated Profit Growth } f[\text{Infrastructure}], \text{Time to Perceive Infrastructure Growth})$

Units: Dimensionless/year

Projected Station Profits $f[\text{Infrastructure}] = (\text{Recent Station Profits } f[\text{Infrastructure}] \times (1 + (\text{Forecast Horizon - Infrastructure} \times \text{Expected growth in Profits } f[\text{Infrastructure}])))$

Units: Dimensionless

Projected profitability forecast

/*******************************************************************************/

Pumps per Station $f[\text{Infrastructure}] = 10, 1, 4, 4$

Units: pump

There are 10 gas pumps per gas station. There is 1 charger per plug station. There are 4 cng and H2 refueling points per station respectively.

Available Refueling Pumps $r[\text{GASOLINEFUEL}] = \text{Gas Station Pump Mix } g[\text{GASOLINEPUMP}] \times \text{Available Infrastructure Pumps } f[\text{GASPUMP}]$

Available Refueling Pumps $r[\text{DIESELFUEL}] = \text{Gas Station Pump Mix } g[\text{DIESELPUMP}] \times \text{Available Infrastructure Pumps } f[\text{GASPUMP}]$
Available Refueling Pumps $r[BIOFUEL] = \text{Gas Station Pump Mix } g[BioPUMP] \times \text{Available Infrastructure Pumps } f[GASPUMP]$

Available Refueling Pumps $r[CNGFUEL] = \text{Available Infrastructure Pumps } f[CNGPUMP]$

Available Refueling Pumps $r[H2FUEL] = \text{Available Infrastructure Pumps } f[H2PUMP]$

Available Refueling Pumps $r[ELECTRICITY] = \text{Available Infrastructure Pumps } f[PLUG]$

Units: pump

*Number of pumps available is product of pumps per station and number of stations. \[
\text{Number of Pumps} = \text{Number of Station} \times \text{Number of Pumps per Station} \times \text{Pump Mix in a Given Station}
\]*

Demand for Infrastructure by Pumps $ir[\text{Technology,Fuels}] = \text{ZIDZ("Fleet Refuels Required per Year by Platform-Fuel } ir[\text{Technology,Fuels}], (\text{Refueling Capacity per Fuel type per Year } ir[\text{Technology,Fuels}]) \}$

Units: pump

*Number of pumps required is required fuels demanded per fleet type divided by the capacity of each pump to deliver the required quantity of fuel. \[
\text{Demand for Infrastructure by Pump } ir[\text{GAS,GASOLINEFUEL}] + \text{Demand for Infrastructure by Pump } ir[\text{Diesel,DIESELFUEL}] + \text{Demand for Infrastructure by Pump } ir[\text{Bio,BIOFUEL}] + \text{Demand for Infrastructure by Pump } ir[\text{HEV,GASOLINEFUEL}] + \text{Demand for Infrastructure by Pump } ir[\text{PHEV,GASOLINEFUEL}]
\]*

Demand for Gas pumps from all the platforms that use gasoline fuel.

Demand for Infrastructure by Pump $ir[\text{BEV,ELECTRICITY}] + \text{Demand for Infrastructure by Pump } ir[\text{PHEV,ELECTRICITY}]$

Demand for Public charging stations from PHEV and BEV platforms.

Demand for Infrastructure by Pump $ir[\text{CNG,CNGFUEL}]$

Demand for Infrastructure by Pump $ir[H2,H2FUEL]$

Demand for Pump by Fuel type $r[\text{Fuels}] = \text{SUM(Demand for Infrastructure by Pumps } ir[\text{Technology!, Fuels}])$

Units: pump

*Demand for each pump type is dependent on all the platforms that use the pump. \[
\text{Demand for Infrastructure } f[GASPUMP] = \text{MAX( ZIDZ(Demand for Pump by Fuel type } r[\text{GASOLINEFUEL}], \text{Gas Station Pump Mix } g[\text{GASOLINEPUMP}] \times \text{Pumps per Station } f[GASPUMP]), \text{MAX(ZIDZ(Demand for Pump by Fuel type } r[\text{DIESELFUEL}], \text{Gas Station Pump Mix } g[\text{DIESELPUMP}] \times \text{Pumps per Station } f[GASPUMP]), ZIDZ(Demand for Pump by Fuel type } r[\text{BIOFUEL}], \text{Gas Station Pump Mix } g[\text{BioPUMP}] \times \text{Pumps per Station } f[GASPUMP]) \})
\]*
Demand for Infrastructure $f[\text{PLUG}]=ZIDZ(\text{Demand for Pump by Fuel type } r[\text{ELECTRICITY}], \text{Pumps per Station } f[\text{PLUG}])$

Demand for Infrastructure $f[\text{CNGPUMP}]=ZIDZ(\text{Demand for Pump by Fuel type } r[\text{CNGFUEL}], \text{Pumps per Station } f[\text{CNGPUMP}])$

Demand for Infrastructure $f[\text{H2PUMP}]=ZIDZ(\text{Demand for Pump by Fuel type } r[\text{H2FUEL}], \text{Pumps per Station } f[\text{H2PUMP}])$

Units: stations

Conversion from pumps demand to station demand

Effect of Profitability on Desired Infrastructure $f[\text{Infrastructure}]=TF$ for Profitability($\text{Ratio of Projected Profit to Target Profitability } f[\text{Infrastructure}])$

Units: Dimensionless

Effect of Utilization on Desired Infrastructure $f[\text{Infrastructure}]=TF$ for Utilization($\text{Ratio of Projected Utilization and Target Utilization } f[\text{Infrastructure}]$)

Units: Dimensionless

Utilization and profitability determine the additional infrastructure required based on the table function and target profitability and target utilization.

Exogenous Infrastructure $f[\text{GASPUMP}]=0$

Exogenous Infrastructure $f[\text{PLUG}]=\text{Stations per Year } f[\text{PLUG}]*(\text{PULSE(MIN(Platform Introduction Date } j[\text{PHEV}], \text{ Platform Introduction Date } j[\text{BEV}])-0.5, \text{ Program Duration } f[\text{PLUG}]))$

Exogenous Infrastructure $f[\text{CNGPUMP}]=\text{Stations per Year } f[\text{CNGPUMP}]*(\text{PULSE( Platform Introduction Date } j[\text{CNG}]-0.5, \text{ Program Duration } f[\text{CNGPUMP}]))$

Exogenous Infrastructure $f[\text{H2PUMP}]=\text{Stations per Year } f[\text{H2PUMP}]*(\text{PULSE( Platform Introduction Date } j[\text{H2}]-0.5, \text{ Program Duration } f[\text{H2PUMP}]))$

Units: stations/year

Program Duration $f[\text{Infrastructure}]=5$

Units: year

Exogenous Infrastructure addition is used to provide infrastructure incentives that are needed to solve the chicken and egg problem.

FE by Platform by Fuel $ir[\text{Technology,Fuels}]=\text{IF THEN ELSE}(\text{Technology }= \text{BEV}, \text{Fuel Usage Matrix } ir[\text{Technology,Fuels}] \times \text{Electricity to Gasoline Efficiency Conversion Factor } EE \times \text{by Platform } i[\text{BEV}], \text{ IF THEN ELSE}((\text{Technology} \neq \text{PHEV} : \text{AND: Fuels } = \text{ELECTRICITY}), \text{Fuel Usage Matrix } ir[\text{Technology,Fuels}] \times \text{Electricity to Gasoline Efficiency Conversion Factor/EE by Platform } i[\text{PHEV}], \text{ Fuel Usage Matrix } ir[\text{Technology,Fuels}] \times \text{FE by Platform } i[\text{Technology}]))$

Units: miles/GGE

Fuel Usage Matrix $ir[\text{Technology,Fuels}]=[1,0,0,0,0,0;1,0,0,0,0,0;1,0,0,0,0,1;0,0,0,0,0,1;0,0,0,0,0,0;0,0,0,0,0,0;0,0,1,0,0,0;1,0,0,0,0,0;0,0,0,1,0,0;0,0,0,0,0,0] $
Units: Dimensionless

*Fuel Usage Matrix ir* is used to establish the Fuel and Platform mapping.

"Fleet Refuels Required per Year by Platform-Fuel ir"[Technology,Fuels]="Refuels per Year by Platform-Fuel ir"[Technology,Fuels]*Installed Base i[Technology]
Units: vehicles/year

\[
\text{Total Fuel Consumed} = \frac{\text{Total Number of Vehicles } \times \text{VKT}}{\text{Fuel Efficiency}}
\]

"Forecast Horizon - Infrastructure"= 1
Units: year

Fuel Dispensing Rate \( r[\text{Fuels}] = [600,600,600,400,400,0.4] \)
Units: GGE/hour

Operating Hours per Year by Fuel \( r[\text{Fuels}] = 3140 \)
Units: hour/year/pump

Maximum Fuel Dispensing Capacity per Pump \( r[\text{Fuels}] = \text{Fuel Dispensing Rate } r[\text{Fuels}] \times \text{Operating Hours per Year by Fuel } r[\text{Fuels}] \)
Units: GGE/year/pump

*Maximum dispensing capacity of a pump is the product of fuel dispensing rate and operating hours per year by the fuel.*

Fuel Consumed Per Pump \( r[\text{Fuels}] = \text{MIN} (\text{Maximum Fuel Dispensing Capacity per Pump } r[\text{Fuels}], \)
\( \text{IF THEN ELSE } ((\text{Fuels} = \text{GASOLINEFUEL}), \text{ZIDZ} (\text{Fuel Consumed per Platform } \text{ir } [\text{GAS,GASOLINEFUEL}] + \text{Fuel Consumed per Platform } \text{ir } [\text{HEV,GASOLINEFUEL}] + \text{Fuel Consumed per Platform } \text{ir } [\text{PHEV,GASOLINEFUEL}], \text{Pumps by Fuel } r[\text{GASOLINEFUEL}]), \)
\( \text{IF THEN ELSE } ((\text{Fuels} = \text{ELECTRICITY}), \text{ZIDZ} (\text{Fuel Consumed per Platform } \text{ir } [\text{BEV,ELECTRICITY}] + \text{Fuel Consumed per Platform } \text{ir } [\text{PHEV,ELECTRICITY}], \text{Pumps by Fuel } r[\text{ELECTRICITY}]), \)
\( \text{ZIDZ} (\text{SUM} (\text{Fuel Consumed per Platform } \text{ir } [\text{Technology!},\text{Fuels}], \text{Pumps by Fuel } r[\text{Fuels}]),)) \))
Units: GGE/year/pump

\[
\text{Fuel Consumed per Pump} = \frac{\text{Total Fuel Consumed}}{\text{Number of Pumps}}
\]

Pump Profits Weight= 0.0005
Units: Dimensionless*pump*year/$
Pump Switch Cost $r[Fuels] = 1000$
Units: $$/pump/year$

Pump Utility $r[Fuels] = $ Switch Cost Weight * Pump Switch Cost $r[Fuels] +$ Pump Profits Weight * Pump Operating Profits $r[Fuels]$
Units: Dimensionless

**Pump utility is the weighted sum of pump profits, pump switch cost**

$$\text{EXP Pump Utility } r[\text{GASOLINEFUEL}] = \text{IF THEN ELSE}(\text{Platform Introduction Date } j[\text{GAS}] \geq \text{Time}, 0, \text{EXP(Pump Utility } r[\text{GASOLINEFUEL}]))$$

$$\text{EXP Pump Utility } r[\text{DIESELFUEL}] = \text{IF THEN ELSE}(\text{Platform Introduction Date } j[\text{Diesel}] \geq \text{Time}, 0, \text{EXP(Pump Utility } r[\text{DIESELFUEL}]))$$

$$\text{EXP Pump Utility } r[\text{BIOFUEL}] = \text{IF THEN ELSE}(\text{Platform Introduction Date } j[\text{Bio}] \geq \text{Time}, 0, \text{EXP(Pump Utility } r[\text{BIOFUEL}]))$$
Units: Dimensionless

**Taking exponent of utility for logit function**

Desired Gas Station Mix $r[\text{GASOLINEPUMP}] = \text{ZIDZ(EXP Pump Utility } r[\text{GASOLINEFUEL}], (\text{EXP Pump Utility } r[\text{GASOLINEFUEL}] + \text{EXP Pump Utility } r[\text{DIESELFUEL}] + \text{EXP Pump Utility } r[\text{BIOFUEL}]))$

Desired Gas Station Mix $r[\text{DIESELPUMP}] = \text{ZIDZ(EXP Pump Utility } r[\text{DIESELFUEL}], (\text{EXP Pump Utility } r[\text{GASOLINEFUEL}] + \text{EXP Pump Utility } r[\text{DIESELFUEL}] + \text{EXP Pump Utility } r[\text{BIOFUEL}]))$

Desired Gas Station Mix $r[\text{BioPUMP}] = \text{ZIDZ(EXP Pump Utility } r[\text{BIOFUEL}], (\text{EXP Pump Utility } r[\text{GASOLINEFUEL}] + \text{EXP Pump Utility } r[\text{DIESELFUEL}] + \text{EXP Pump Utility } r[\text{BIOFUEL}]))$
Units: Dimensionless

**Logit function that describes the pump owner’s desired gas station pump mix. If a particular pump is more profitable than the pump of the other platform and the switching cost is minimal then the owner makes a switch to the pump of maximum utility.**

Gas Station Pump Mix $g[\text{Gaspumpmix}] = \text{INTEG ( Rate of Change of Gas Station Mix } r[\text{Gaspumpmix}], \text{Initial Gas Station Mix } r[\text{Gaspumpmix}])$
Units: Dimensionless

**Gas pump mix is a stock that changes at the Rate of Change of Gas Station Mix. Initial Gas station mix is given by the variable Initial Gas Station Mix**

Normalized Station profit Margin $f[\text{Infrastructure}] = \text{ZIDZ(Station Profit } f[\text{Infrastructure}], (\text{Station Fixed Costs } f[\text{Infrastructure}] + \text{Stations Operating Costs } f[\text{Infrastructure}]))$
Units: Dimensionless

**A station margin is the total station profits divided by the total station costs.**
Pumps by Fuel \( r[\text{GASOLINEFUEL}] = \text{Available Infrastructure} \times \text{Gas Station Pump Mix} \times \text{Pumps per Station} \times \text{GASPUMP} \)

Pumps by Fuel \( r[\text{DIESELFUEL}] = \text{Available Infrastructure} \times \text{Gas Station Pump Mix} \times \text{DIESELPU MULTS} \times \text{Pumps per Station} \times \text{GASPUMP} \)

Pumps by Fuel \( r[\text{BIOFUEL}] = \text{Available Infrastructure} \times \text{Gas Station Pump Mix} \times \text{BioPUMP} \times \text{Pumps per Station} \times \text{GASPUMP} \)

Pumps by Fuel \( r[\text{CNGFUEL}] = \text{Available Infrastructure} \times \text{CNGPUMP} \times \text{Pumps per Station} \times \text{CNGPUMP} \)

Pumps by Fuel \( r[\text{H2FUEL}] = \text{Available Infrastructure} \times \text{H2PUMP} \times \text{Pumps per Station} \times \text{H2PUMP} \)

Pumps by Fuel \( r[\text{ELECTRICITY}] = \text{Available Infrastructure} \times \text{PLUG} \times \text{Pumps per Station} \times \text{PLUG} \)

Units: pump

Pumps by fuel are product of available infrastructure gas station pump mix and pumps per station.

Recent Station Profits \( f[\text{Infrastructure}] = \text{SMOOTH} (\text{Normalized Station profit Margin} \times f[\text{Infrastructure}], \text{Infrastructure Perception Time}) \)

Units: Dimensionless

Recent station profits are a smooth function of Normalized station profit margin.

Recent Utilization \( f[\text{Infrastructure}] = \text{SMOOTH} (\text{Infrastructure Utilization} \times f[\text{Infrastructure}], \text{Infrastructure Perception Time}) \)

Units: Dimensionless

Recent station utilization are a smooth function of Infrastructure Utilization \( f \) over the perception time.

Refueling Capacity \( r[\text{GAS}, \text{Fuels}] = \text{IF THEN ELSE} (\text{Fuels} = \text{GASOLINEFUEL}, \text{Effective Range} \times \text{GASFUEL} \times \text{FE} \times \text{Platform} \times \text{Fuel} \times \text{GASFUEL}, 0) \)

Refueling Capacity \( r[\text{HEV}, \text{Fuels}] = \text{IF THEN ELSE} (\text{Fuels} = \text{GASOLINEFUEL}, \text{Effective Range} \times \text{HEVFUEL} \times \text{FE} \times \text{Platform} \times \text{Fuel} \times \text{HEVFUEL}, 0) \)

Refueling Capacity \( r[\text{PHEV}, \text{Fuels}] = \text{IF THEN ELSE} (\text{Fuels} = \text{GASOLINEFUEL}, \text{Effective Range} \times \text{PHEVFUEL} \times \text{FE} \times \text{Platform} \times \text{Fuel} \times \text{PHEVFUEL}, 0) \)

Refueling Capacity \( r[\text{BEV}, \text{Fuels}] = \text{IF THEN ELSE} (\text{Fuels} = \text{ELECTRICITY}, \text{Effective Range} \times \text{BEVFUEL} \times \text{FE} \times \text{Platform} \times \text{Fuel} \times \text{BEVFUEL}, 0) \)

Refueling Capacity \( r[\text{CNG}, \text{Fuels}] = \text{IF THEN ELSE} (\text{Fuels} = \text{CNGFUEL}, \text{Effective Range} \times \text{CNGFUEL} \times \text{FE} \times \text{Platform} \times \text{Fuel} \times \text{CNGFUEL}, 0) \)

Refueling Capacity \( r[\text{Diesel}, \text{Fuels}] = \text{IF THEN ELSE} (\text{Fuels} = \text{DIESELFUEL}, \text{Effective Range} \times \text{DIESEL FUEL} \times \text{FE} \times \text{Platform} \times \text{Fuel} \times \text{DIESEL FUEL}, 0) \)

Refueling Capacity \( r[\text{H2}, \text{Fuels}] = \text{IF THEN ELSE} (\text{Fuels} = \text{H2FUEL}, \text{Effective Range} \times \text{H2FUEL} \times \text{FE} \times \text{Platform} \times \text{Fuel} \times \text{H2FUEL}, 0) \)

66
Refueling Capacity \( \text{ir[Bio,Fuels]} \) = IF THEN ELSE(Fuels=BIOFUEL, Effective Range \( \text{ir[Bio,Fuels]} \)/FE by Platform by Fuel \( \text{ir[Bio,Fuels]} \), 0)
Units: GGE/vehicles

*Refueling capacity is effective range divided by fuel efficiency by fuel platform.*

Refueling Time \( \text{ir[Technology,Fuels]} \) = ZIDZ(Refueling Capacity \( \text{ir[Technology,Fuels]} \), Fuel Dispensing Rate \( r[Fuels] \) ) + Transaction Time by Fuel \( r[Fuels] \)*Fuel Usage Matrix \( \text{ir[Technology,Fuels]} \)
Units: hour/vehicles

*The total time to refuel a vehicle is tank capacity divided by fuel dispensing rate of the pump plus the transaction time at the fueling pump.*

Refueling Capacity per Fueltype per Year \( \text{ir[Technology,Fuels]} \) = ZIDZ(Operating Hours per Year by Fuel \( r[Fuels] \), Refueling Time \( \text{ir[Technology,Fuels]} \) )
Units: vehicles/pump/year

*The number of vehicles that a pump can serve is determined by dividing the operating hours per year by fuel divided by the refueling time.*

"Refuels per Year by Platform-Fuel \( \text{ir[Technology,Fuels]} \)" = ZIDZ(VMT Public per Year by Platform and by Fuel \( \text{ir[Technology,Fuels]} \), Effective Range \( \text{ir[Technology,Fuels]} \))
Units: Dimensionless/year

*Refuels per Year by Platform-Fuel \( \text{ir} \) is determined by dividing vehicle miles travelled by Effective Range \( \text{ir} \)*

Supply Line Adjustment Time \( f[Infrastructure] \) = 2
Units: year

Target Profitability \( f[Infrastructure] \) = 0.1
Units: Dimensionless

*Target profitability is determined based on sensitivity analysis.*

Target Utilization= 0.02
Units: Dimensionless

*Target utilization is determined based on the sensitivity analysis.*

TF for Profitability\(((\{-5,0\},\{-10,10\}),\{-5,0.1\},\{-4,0.1\},\{-3,0.1\},\{-2,0.1\},\{-1,0.1\},\{0,0.6\},\{1,1\},\{2,1.4\},\{3,1.7\},\{4,1.7\},\{5,1.7\})\)
Units: Dimensionless
TF for Utilization\([[(0,0);(10,3)],(0,0),(0.5,0.33),(1,1),(1.5,1.6),(2,1.9),(2.5,2.15),(3,2.2),(3.5,2.3) ,\), (4,2.3),(4.5,2.3),(5,2.3)]\)
Units: Dimensionless

Time to Perceive Infrastructure Growth=1
Units: year

Transaction Time by Fuel \(r[Fuels]\) = 0.083
Units: hour/vehicles

//**************************Station and Pump Economics***************************/

Pump Costs \(r[Fuels]\) = Feedstock Cost \(r[Fuels]\)*Fuel Consumed Per Pump \(r[Fuels]\)+Fuel Consumed Per Pump \(r[Fuels]\)*Pump Operating Cost \(r[Fuels]\)
Units: $/pump/year
Pump Operating Cost \(r[Fuels]\)=0.005
Units: $/GGE

*Pump costs is the sum of feedstock costs and operating costs.*

Feedstock Cost \(r[Fuels]\)= Retail Fuel Price \(r[Fuels]\)/\((1+Retail Markup \(r[Fuels]\))
Units: $/GGE
Pump Fuel Revenues \(r[Fuels]\)= Fuel Consumed Per Pump \(r[Fuels]\)*Retail Fuel Price \(r[Fuels]\)
Units: $/pump/year
Pump Operating Profits \(r[Fuels]\)=Pump Fuel Revenues \(r[Fuels]\)-Pump Costs \(r[Fuels]\)
Units: $/pump/year

Operating Profits per pump = Fuel Consumed per Pump * Profit Margin

Station Fixed Costs \(f[Infrastructure]\)= 9000,250,250,10000
Units: $/(year*stations)

*Station fixed costs are amortized over the lifetime of the refueling infrastructure*

Station Profit \(f[GASPUMP]\)= (Gas Station Pumps Available \(g[GASolinePUMP]\)*Pump Operating Profits \(r[GASolineFUEL]\)+Gas Station Pumps Available \(g[DIESELPUMP]\)*Pump Operating Profits \(r[DIESELFUEL]\)+Gas Station Pumps Available \(g[BioPUMP]\)*Pump Operating Profits \(r[BIOFUEL]\)+Ancillary Revenues Per Station[GASPUMP]-Station Fixed Costs \(f[GASPUMP]\) + Infrastructure Incentive Value \(f[GASPUMP]\)
Station Profit $f_{CNGPUMP} = \text{IF THEN ELSE} (\text{Platform Introduction Date } j_{CNG} > \text{Time}, 0, \text{Pumps per Station } f_{CNGPUMP} \times \text{Pump Operating Profits } r_{CNGFUEL} + \text{Ancillary Revenues Per Station } f_{CNGPUMP} - \text{Station Fixed Costs } f_{CNGPUMP} + \text{Infrastructure Incentive Value } f_{CNGPUMP})$

Station Profit $f_{H2PUMP} = \text{IF THEN ELSE} (\text{Platform Introduction Date } j_{H2} > \text{Time}, 0, \text{Pumps per Station } f_{H2PUMP} \times \text{Pump Operating Profits } r_{H2FUEL} + \text{Ancillary Revenues Per Station } f_{H2PUMP}$

Station Profit $f_{PLUG} = \text{IF THEN ELSE} (\text{Platform Introduction Date } j_{PHEV} > \text{Time}, 0, \text{Pump Operating Profits } r_{ELECTRICITY} \times \text{Pumps per Station } f_{PLUG} + \text{Ancillary Revenues Per Station } f_{PLUG} - \text{Station Fixed Costs } f_{PLUG} + \text{Infrastructure Incentive Value } f_{PLUG})$

Units: $/\text{stations/year}$

Station profits are pump operating profits times the number of pumps plus the ancillary revenues per station minus the station fixed cost. Any infrastructure incentives are also subtracted from the station costs.

The vehicle price and the battery cost evolution follow a standard learning curve.

Annual CO2 Emissions by Platform $i_{[Technology]} = \text{Annual Emissions by Platform } i_{[Technology]}$
Units: tonnes CO2e/year

Annual Emissions by Platform $i_{[Technology]} = \text{Annual Manufacturing Emissions by Platform } i_{[Technology]} + \text{Annual Operating Emissions by Platform } i_{[Technology]} + \text{Annual Recycling/Disposal Emissions by Platform } i_{[Technology]}$
Units: tonnes CO2e/year

Total lifecycle emissions of AFVs is calculated per platform by adding the emissions during manufacturing operating and disposing the vehicle.

Annual Manufacturing Emissions by Platform $i_{[Technology]} = \text{Vehicle Manufacturing } i_{[Technology]} + \text{Battery Manufacturing } i_{[Technology]}$
Units: tonnes CO2e/year

Manufacturing emissions has two components: Vehicle manufacturing and battery manufacturing.

Annual Miles by Platform $i_{[Technology]} = \text{Installed Base } i_{[Technology]} \times \text{VMT per Year } i_{[Technology]}$
Units: miles/year
Annual Operating Emissions by Platform i[Technology]= Annual Miles by Platform i[Technology]*Emissions per Mile i[Technology]
Units: tonnes CO2e/year

*Operating emissions is Miles travelled times the emissions per mile.*

Units: tonnes CO2e/year

Battery Manufacturing i[Technology]= Battery i[Technology]*Order Fulfillment j[Technology]*GHG Emissions per Unit Battery Manufactured
Units: tonnes CO2e/year

Cumulative CO2 Emissions by Platform i[Technology]= INTEG (Annual CO2 Emissions by Platform i[Technology], 0)
Units: tonnes CO2e/year

*Cumulative emissions are the integral of the emissions per platform.*

EE by Platform i[PHEV]= PHEV Energy Efficiency
EE by Platform i[BEV]= BEV Energy Efficiency
Units: kW*hour/miles

Emission per Mile PHEV i[Technology]= IF THEN ELSE(Technology=PHEV, (% All Electric Miles by Installed Base Platform i'[Technology]*Emissions per Mile Electric i[Technology])+(1-% All Electric Miles by Installed Base Platform i'[Technology])*Emissions per Mile Gasoline i[GAS], 0)
Units: tonnes CO2e/miles

Emissions per Mile BEV i[Technology]= IF THEN ELSE(Technology=BEV, Emissions per Mile Electric i[Technology], 0)
Units: tonnes CO2e/miles

Emissions per Mile CNG i[TechnologyTo]= IF THEN ELSE(TechnologyTo=CNG, ZIDZ(GHG Emissions Factor r[CNGFUE]}, Average FE by Platform i[TechnologyTo]), 0)
Units: tonnes CO2e/miles

Emissions per Mile Diesel i[TechnologyTo]= IF THEN ELSE(TechnologyTo=Diesel, ZIDZ(GHG Emissions Factor r[DIESELFUEL],Average FE by Platform i[TechnologyTo]), 0)
Units: tonnes CO2e/miles
Emissions per Mile Electric $i[Technology]$ = "GHG Emissions Factor - Electricity" * EE by Platform $i[Technology]$
Units: tonnes CO2e/miles

Emissions per Mile Ethanol $i[Technology]$ = IF THEN ELSE (Technology = Bio, ZIDZ(GHG Emissions Factor $r[BIOFUEL], Average FE by Platform $i[Technology]$), 0)
Units: tonnes CO2e/miles

Emissions per Mile Gasoline $i[Technology]$ = IF THEN ELSE (Technology = GAS, ZIDZ(GHG Emissions Factor $r[GASOLINEFUEL], Average FE by Platform $i[Technology]$), 0)
Units: tonnes CO2e/miles

Emissions per Mile Gasoline $j[TechnologyTo]=$
IF THEN ELSE (TechnologyTo = GAS, ZIDZ(GHG Emissions Factor $r[GASOLINEFUEL], FE by Platform $i[Technology]$), 0)
~ tonnes CO2e/miles
~

Emissions per Mile H2 $i[Technology]$ = IF THEN ELSE (Technology = H2, ZIDZ(GHG Emissions Factor $r[H2FUEL], Average FE by Platform $i[Technology]$), 0)
Units: tonnes CO2e/miles

Emissions per Mile HEV $j[TechnologyTo]=$ IF THEN ELSE (TechnologyTo = HEV, ZIDZ(GHG Emissions Factor $r[GASOLINEFUEL], FE by Platform $i[Technology]$), 0)
Units: tonnes CO2e/miles

$Emissions per Mile \ i / j = GHG Emissions Factor \ i / j \ divided \ by \ the \ FE \ by \ Platform \ i / j$

Emissions per Mile of BEV $j[TechnologyTo]=$ IF THEN ELSE (TechnologyTo = BEV, Emissions per Mile Electric $i[Technology]$ , 0)
Units: tonnes CO2e/miles

Emissions per Mile of CNG $j[TechnologyTo]=$ IF THEN ELSE (TechnologyTo = CNG, ZIDZ(GHG Emissions Factor $r[CNGFUEL], FE by Platform $i[Technology]$), 0)
Units: tonnes CO2e/miles

Emissions per Mile of Diesel $j[TechnologyTo]=$ IF THEN ELSE (TechnologyTo = Diesel, ZIDZ(GHG Emissions Factor $r[DIselFUEL], FE by Platform $i[Technology]$), 0)
Units: tonnes CO2e/miles
Emissions per Mile of Ethanol \([\text{TechnologyTo}]\) = IF THEN ELSE(\(\text{TechnologyTo} = \text{Bio}\), \(ZIDZ(\text{GHG Emissions Factor} \ r[\text{BIOFUEL}], \text{FE by Platform} \ i[\text{TechnologyTo}]), 0)\)
Units: tonnes CO2e/miles

Emissions per Mile of H2 \([\text{TechnologyTo}]\) = IF THEN ELSE(\(\text{TechnologyTo} = \text{H2}\), \(ZIDZ(\text{GHG Emissions Factor} \ r[\text{H2FUEL}], \text{FE by Platform} \ i[\text{TechnologyTo}]), 0)\)
Units: tonnes CO2e/miles

Emissions per Mile of HEV \([\text{Technology}]\) = IF THEN ELSE(\(\text{Technology} = \text{HEV}\), \(ZIDZ(\text{GHG Emissions Factor} \ r[\text{GASOLINEFUEL}], \text{Average FE by Platform} \ i[\text{Technology}]), 0)\)
Units: tonnes CO2e/miles

Emissions per Mile PHEV \([\text{TechnologyTo}]\) = IF THEN ELSE(\(\text{TechnologyTo} = \text{PHEV}\), \(\frac{\% \text{ All Electric Miles by Platform} \ j[\text{TechnologyTo}]}{\% \text{ All Electric Miles by Platform} \ j[\text{TechnologyTo}]} \times \text{Emissions per Mile Electric} \ i[\text{TechnologyTo}] + (1 - \frac{\% \text{ All Electric Miles by Platform} \ j[\text{TechnologyTo}])} \times \text{Emissions per Mile Gasoline} \ j[\text{GAS}], 0)\)
Units: tonnes CO2e/miles

Emissions per Mile \([\text{Technology}]\) =
\[\text{Emissions per Mile CNG} \ i[\text{Technology}] + \text{Emissions per Mile Diesel} \ i[\text{Technology}] + \text{Emissions per Mile Ethanol} \ i[\text{Technology}] + \text{Emissions per Mile H2} \ i[\text{Technology}] + \text{Emissions per Mile PHEV} \ i[\text{Technology}] + \text{Emissions per Mile of HEV} \ i[\text{Technology}] + \text{Emissions per Mile Gasoline} \ i[\text{Technology}] + \text{Emissions per Mile BEV} \ i[\text{Technology}]\]
Units: tonnes CO2e/miles

Emissions per Mile \([\text{TechnologyTo}]\) =
\[\text{Emissions per Mile Gasoline} \ j[\text{TechnologyTo}] + \text{Emissions per Mile HEV} \ j[\text{TechnologyTo}] + \text{Emissions per Mile of CNG} \ j[\text{TechnologyTo}] + \text{Emissions per Mile of Diesel} \ j[\text{TechnologyTo}] + \text{Emissions per Mile of Ethanol} \ j[\text{TechnologyTo}] + \text{Emissions per Mile of H2} \ j[\text{TechnologyTo}] + \text{Emissions per Mile PHEV} \ j[\text{TechnologyTo}] + \text{Emissions per Mile of BEV} \ j[\text{TechnologyTo}]\]
Units: tonnes CO2e/miles

"GHG Emissions Factor - CNG" = 0.0069
Units: tonnes CO2e/gallon
"GHG Emissions Factor - Diesel" = 0.01021
Units: tonnes CO2e/gallon

"GHG Emissions Factor - Electricity" = IF THEN ELSE( SW Electricity Source = 0, "GHG Emissions Factor - Grid Mix", "GHG Emissions Factor - Renewables")
Units: tonnes CO2e/(kW*hour)

"GHG Emissions Factor - Ethanol" = 0.00575
Units: tonnes CO2e/gallon

"GHG Emissions Factor - Gasoline" = 0.00891
Units: tonnes CO2e/gallon

"GHG Emissions Factor - Grid Mix" = 0.000684
Units: tonnes CO2e/(kW*hour)

"GHG Emissions Factor - Hydrogen" = 0.015
Units: tonnes CO2e/gallon

"GHG Emissions Factor - Renewables" = 0
Units: tonnes CO2e/(kW*hour)

GHG Emissions Factor r[GASOLINEFUEL] = "GHG Emissions Factor - Gasoline"*Native units to GGE Gasoline
GHG Emissions Factor r[DIESELFUEL] = "GHG Emissions Factor - Diesel"*Native units to GGE Diesel
GHG Emissions Factor r[BIOFUEL] = "GHG Emissions Factor - Ethanol"*Native units to GGE E85
GHG Emissions Factor r[CNGFUEL] = "GHG Emissions Factor - CNG"*Native units to GGE CNG
Correction Factor
GHG Emissions Factor r[H2FUEL] = "GHG Emissions Factor - Hydrogen"*Native units to GGE H2
Correction Factor
GHG Emissions Factor r[ELECTRICITY] = "GHG Emissions Factor - Electricity"*Native units to GGE Electricity
Units: tonnes CO2e/GGE

to	
tonnes CO2e/GGE to tonnes CO2e/gallon conversion

GHG Emissions per Unit Battery Manufactured = 0.12
Units: tonnes CO2e/(kW*hour)
GHG Emissions per Vehicle Manufactured= 8.5
Units: tonnes CO2e/vehicles

GHG Emissions per Vehicle Retired= 1.14
Units: tonnes CO2e/vehicles

Total Annual CO2 Emissions= SUM(Annual Emissions by Platform i[Technology!])
Units: tonnes CO2e/year

Total annual emissions are the sum of emissions from each platform.

Total Cumulative CO2 Emissions= INTEG (Total Annual CO2 Emissions,0)
Units: tonnes CO2e

Cumulative emission is the integral of total annual co2 emissions.

"2000 CO2 Emissions" = INITIAL(Total Annual CO2 Emissions)
Units: tonnes CO2e/year

"% Change in CO2 Emissions"= (Total Annual CO2 Emissions-"2000 CO2 Emissions")/"2000 CO2 Emissions"
Units: dmnl

Change in CO2 Emissions = Total Annual CO2 Emissions - 2000 CO2 Emissions
Appendix- B : Simulation

All Sensitivity analysis and simulations are performed on Vensim 6.0 b DSS for Windows

Simulation Control Parameters

FINAL TIME = 2050
Units: year
INITIAL TIME = 2000
Units: year
SAVEPER = TIME STEP
TIME STEP = 0.015625
INTEGRATION TYPE = EULER

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Figure #</th>
<th>Settings</th>
<th>Simulated Variable</th>
<th>Subscripts</th>
</tr>
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<tbody>
<tr>
<td>GDP Growth Rate</td>
<td>Figure 9</td>
<td>GDP SW : LOW, MED, HIGH</td>
<td>GDP</td>
<td>GDP</td>
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<tr>
<td>Population Growth Rate</td>
<td>Figure 10</td>
<td>Pop SW: LOW, MED, HIGH</td>
<td>Population</td>
<td>Population</td>
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<tr>
<td>Retail Fuel Price</td>
<td>Figure 13</td>
<td>None</td>
<td>Retail Fuel Price r</td>
<td>Fuels</td>
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</table>
| Total Installed Base        | Figure 14| Low Growth:
GDP SW = LOW
Pop SW = HIGH
Average Growth:
GDP SW = MED
Pop SW = MED
High Growth:
GDP SW = HIGH
Pop SW = LOW | Total Installed Base |
| Base Case Scenario          | Figure 15| Incentive Value j=0
Spending by Platform j = 50
million/year
Marketing Duration =10 years | Installed Base | Technology |
| Base Case Scenario          | Figure 16| Incentive Value j=0
Spending by Platform j = 50
million/year
Marketing Duration =10 | Available Refueling Pumps r | Fuels      |
<table>
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<th>Simulation</th>
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<th>Settings</th>
<th>Simulated Variable</th>
<th>Subscripts</th>
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<td>Infrastructure)</td>
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<td>years</td>
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<tr>
<td>Base Case Scenario (Station Profits)</td>
<td>Figure 16</td>
<td>Incentive Value j=0</td>
<td>Station Profit</td>
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<td>Base Case Scenario (Annual GHG Emissions by Platform)</td>
<td>Figure 16</td>
<td>Incentive Value j=0</td>
<td>Annual Emissions by Platform</td>
<td>Technology</td>
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<td>Base Case Scenario (Effective Price j)</td>
<td>Figure 16</td>
<td>Incentive Value j=0</td>
<td>Effective Vehicle Price</td>
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<td>NEMMP Case Scenario (Sales)</td>
<td>Figure 17</td>
<td>Incentive Value j[HEV]=1000</td>
<td>Vehicle Sales</td>
<td>Technology</td>
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<tr>
<td>NEMMP Case Scenario (Installed Base)</td>
<td>Figure 18</td>
<td>Incentive Value j[HEV]=1000</td>
<td>Installed Base</td>
<td>Technology</td>
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<tr>
<td>NEMMP Case</td>
<td>Figure 19</td>
<td>Incentive Value j[HEV]=1000</td>
<td>Available Fuels</td>
<td>Fuels</td>
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<tr>
<td>Scenario (Available Refueling Infrastructure)</td>
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<td>Incentive Value $j_{[\text{PHEV}]}=2000$ Incentive Value $j_{[\text{BEV}]}=3000$ Stations Per Year $f_{[\text{PLUG}]}=500$ Spending by Platform $j=50$</td>
<td>Refueling Pumps $r$</td>
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<tr>
<td>NEMMP Scenario (Annual GHG Emissions by Platform)</td>
<td>Figure 20</td>
<td>Incentive Value $j_{[\text{HEV}]}=1000$ Incentive Value $j_{[\text{PHEV}]}=2000$ Incentive Value $j_{[\text{BEV}]}=3000$ Stations Per Year $f_{[\text{PLUG}]}=500$ Spending by Platform $j=50$</td>
<td>Annual Emissions by Platform $i$</td>
<td>Technology</td>
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<tr>
<td>NEMMP Scenario (Battery Cost)</td>
<td>Figure 21</td>
<td>Incentive Value $j_{[\text{HEV}]}=1000$ Incentive Value $j_{[\text{PHEV}]}=2000$ Incentive Value $j_{[\text{BEV}]}=3000$ Stations Per Year $f_{[\text{PLUG}]}=500$ Spending by Platform $j=50$</td>
<td>Battery Cost $i$</td>
<td>HEV,PHEV,BEV</td>
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<tr>
<td>CNG Scenario (Sales and Installed Base)</td>
<td>Figure 22</td>
<td>Incentive Value $j_{[\text{HEV}]}=1000$ Incentive Value $j_{[\text{PHEV}]}=2000$ Incentive Value $j_{[\text{BEV}]}=3000$ Stations Per Year $f_{[\text{PLUG}]}=500$ Stations Per Year $f_{[\text{PLUG}]}=300$ Initial Light Vehicle Market Size $j_{[\text{CNG}]}=100,000$ Spending by Platform $j=50$</td>
<td>Installed Base $i$ Vehicle Sales $i$</td>
<td>Technology</td>
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<tr>
<td>CNG Scenario (Refueling Infrastructure)</td>
<td>Figure 23</td>
<td>Incentive Value $j_{[\text{HEV}]}=1000$ Incentive Value $j_{[\text{PHEV}]}=2000$ Incentive Value $j_{[\text{BEV}]}=3000$ Stations Per Year $f_{[\text{PLUG}]}$</td>
<td>Available Refueling Pumps $r$</td>
<td>Fuels</td>
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### Simulation Figure

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<td>=500</td>
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<tr>
<td>Stations Per Year f [PLUG] =300</td>
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<tr>
<td>Initial Light Vehicle Market Size j [CNG] = 100,000</td>
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### CNG Scenario (Annual GHG Emissions per Platform i)

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<td>Incentive Value j[BEV]=3000</td>
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<tr>
<td>Stations Per Year f [PLUG] =500</td>
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<tr>
<td>Stations Per Year f [PLUG] =300</td>
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### Table 7: Simulation Parameter Settings

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<td>Figure 23</td>
<td>Incentive Value j[HEV]=1000</td>
<td>Annual Emissions by Platform i</td>
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### Sensitivity Analysis

#### Multivariate Sensitivity of Total Installed Base to Population Growth Constant Alpha and Beta (Figure: 8)

<table>
<thead>
<tr>
<th>Population Growth Const</th>
<th>Root Square Error To Historical Data</th>
<th>del</th>
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<tr>
<td></td>
<td>0.37</td>
<td>0.35</td>
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<tr>
<td>13</td>
<td>867208.2</td>
<td>1048416</td>
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<tr>
<td>12.8</td>
<td>1218472</td>
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<tr>
<td>12.6</td>
<td>1774322</td>
<td>1285500</td>
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Table 8: Sensitivity Analysis of Total Installed Base
Vary Population Growth Const from 13 to 12 in steps of 0.1 (Population Growth Const = VECTOR (12, 13, 0.1)). Vary del from 0.3 to 0.4 in steps of 0.01 (del = VECTOR (0.3, 0.4, 0.01)) Observe variable Total Installed Base.

**Multivariate Sensitivity Analysis to Determine Purchase Price Weight and Operating Cost Weight (Figure: 11)**

Vary Purchase Price Weight from -0.9 to 0.7 in steps of 0.01 (Purchase Price Weight = VECTOR (-0.9, -0.7, 0.01)). Vary Operating Cost Weight from 0.3 to 0.2 in steps of 0.025 (Operating Cost Weight = VECTOR (0.3, 0.2, 0.025)) Observe variable Installed Base [DIESEL] for year 2011.

**Multivariate Sensitivity Analysis to Determine Target Profitability and Target Utilization of Refueling Infrastructure (Figure: 12)**

Vary Target Profitability from 0.04 to 0.2 in steps of 0.02 (Target Profitability = VECTOR (0.04, 0.2, 0.02)). Vary Target Utilization from 0.01 to 0.05 in steps of 0.01 (Operating Cost Weight = VECTOR (0.01, 0.05, 0.01)) Observe variable Available Infrastructure f [GAS PUMP].