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SYSTEM DYNAMICS MODELING OF NEW VEHICLE ARCHITECTURE ADOPTION

Carlos Gorbea, Udo Lindemann, Olivier de Weck

ABSTRACT

This paper presents a system dynamics simulation model used to predict the market share penetration of hybrid (HEV) and battery electric vehicles (BEV) over time. The utility of the model for early design decision making stems from its ability to link key influencing factors such as: fuel price fluctuations, government incentives, customer network effects, vehicle cost of ownership/operation and initial retail price differences between alternative vehicles to the internal combustion engine (ICE) reference architecture in a transparent mathematical formulation. The simulation model is set to the 2010 conditions of the light duty vehicle market in the United States and run for a period of ten years from 2010-2020. After 200 iterations with varying fuel prices, the simulation results predict that by 2020 market advances of hybrid cars will go from 4.5% to roughly 14% and electric cars from 0% to roughly 5% market share of new vehicles sold. The estimated figures presented are in line with previously published market analyst estimates. Additionally, the model has the added advantage of experimenting on how influencing factors affect the simulation results.

Keywords: System Dynamics, Vehicle Architectures, Simulation

1 INTRODUCTION

In recent years, automotive manufacturers looking to establish themselves in new or less crowded market spaces have turned to the electrification of powertrains through private and government investment. In 2009, France alone committed over 1.5 Billion Euros towards bringing 2 million electric and hybrid vehicles to market by 2020, with Renault -Nissan committing an additional 4 billion in research and development [1]. The introduction of new vehicle architectures is a costly undertaking. However, the benefits of differentiation have already attracted a new niche market that is projected to capture increasing market share and further open new complementary industries.

Figure 1 shows the expected market growth of hybrid and electric powertrains estimated from different sources [2], [3], [4], [5]. According to the figure, the electrification of vehicle powertrains will be responsible for roughly 20% of new cars sold worldwide by 2020. In the first three projection studies, micro hybrids are added as a conventional vehicle architecture including both otto and diesel engine cars. In contrast, the last two Boston Consulting Group (BCG) studies include micro hybrids along with the hybrid vehicle percentage. The conventional vehicle percentages for the BCG studies are detailed to include gasoline cars under the designation “otto” and “diesel” for compression ignition conventional cars.

In the United States where, gasoline engines dominate the market, mild and full gasoline hybrids are expected to continue to increase in sales and lock in most of the alternative powertrain market. According to the studies in figure 1, Plug-in hybrids (PHEV) and electric cars that will require external charging are expected to gain up to 6 - 10% of the new US car fleet by 2020.

In Europe, the high penetration rate of diesel vehicles reduces the attractiveness of gasoline-hybrids as both technologies offer comparable fuel consumption. Micro hybrid architectures that are compatible with both gasoline and diesel cars will dominate the European market with an expected penetration rate of 5% already by 2012 due to the stringent emission norms and the voluntary European Automobile Manufacturers’ Association (ACEA) agreement signed by all European manufacturing firms [6].

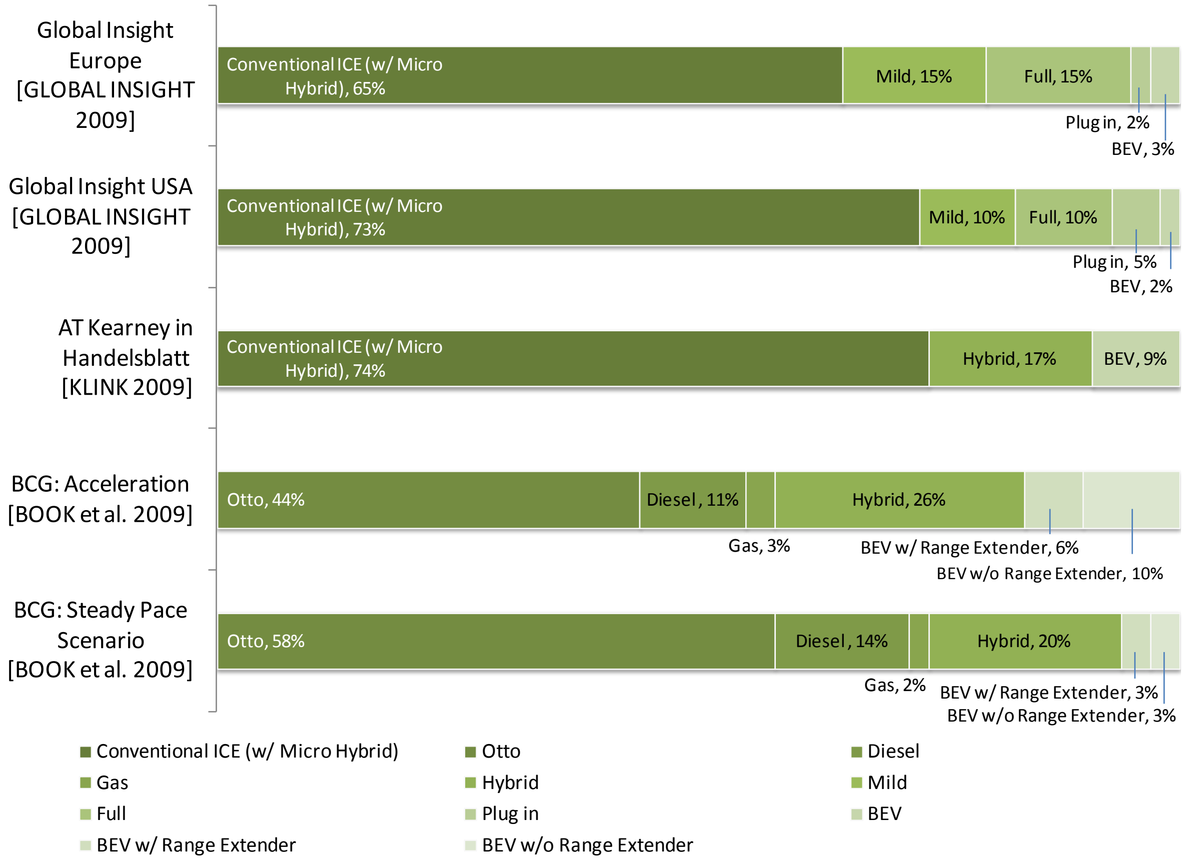

Figure 1 Various market share projections of vehicle powertrains by 2020

2. SYSTEM DYNAMICS METHODOLOGY ACCORDING TO FORRESTER

The firm's business strategy must be flexible to changes in the internal and external context it finds itself in and be ready for asset allocation or asset deployment as conditions change with time. The complexity of business actions can be modeled using the system dynamics methodology. This methodology uses a modeling approach to understand complex systems that is based on stocks (state variables that accumulate and can be measured as levels), flows (rates of change) and feedback loops (circular flows amongst variables) [[8], pp.192-200]. The basic steps of the system dynamics methodology are described below:

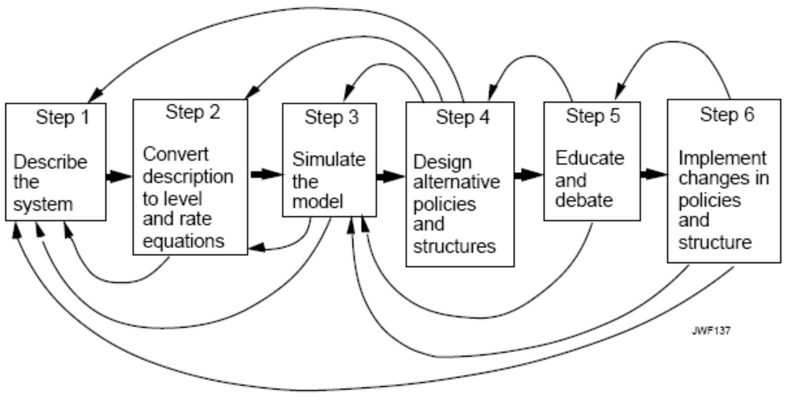

Figure 2 System Dynamics methodology steps according to [7]

Figure 2 shows the stepwise progression from system description to policy implementation that features a number of necessary iterations [7]. The methodology begins with a description of system elements relevant to the problem at hand. The modeling process begins in step 2 by synthesizing the system description into stocks, flows and feedback loops with equations. The simulation in step 3 allows for insight on how the system reacts to input variables overtime and allows for further refinement of steps 1 and 2 in an iterative process. The deepened understanding of the system through step 3 leads to policy creation and debate in steps 4 and 5 that can be tested in the simulation model. Finally, a close look at the effects of policy implementation over time can lead to further model adjustments and validation.

The methodology is an ongoing process that can significantly aid in understanding complex environments and supporting decision making through modeling. As with any modeling technique, the simulation tool is an approximation of the real world and will never account for all the uncertainties and risks inherent in real world situations.

3. MODELING THE ADOPTION OF NEW VEHICLE ARCHITECTURES

The methodology according to Forrester [7] is applied here to the dynamics of new vehicle architecture adoption in the automotive market. The steps of the methodology are developed in a practical example that presents a complex network of business dynamics that can help explain new car architectures adoption scenarios. As the methodology is developed, many of the iteration between steps presented in Figure 2 are left out of the discussion. The simulation model is built using Sterman’s work [[8], pp.392-403] as a reference.

The aim of the model presented in figure 3 is to explain market network effects and other factors that make the adoption of new vehicle architectures more (or less) attractive in the future. Most of the items in the model have already been discussed in this chapter and are revisited here in a simulation model. In order to follow the modeling logic a few basic rules are explained in table 1.

Table 1 Logic symbols in system dynamics model according to [8], pp.139, 194

The elements in a system dynamics model are linked by directional arrows with either positive (+) or negative (-) polarity. A connection between two elements with positive polarity describes a cause and effect type relationship that increases or decreases in the same direction for both elements over time. For example, if we define *product attractiveness* and *product market share* as elements that have a relationship with positive polarity, it simply states that when the product attractiveness increases over time it has an increasing effect on the product market share. Symbolically this is represented by placing the cause element at the arrow base and the effect element at the arrowhead with a '+'sign over it as seen on table 1.

In contrast, a relationship between two elements in a system dynamics model with negative polarity results in opposite effects developing over time. For example, the higher the *cost of operation* a product exhibits over time results in lower overall *product attractiveness*. Likewise, the depiction of this dependency is provided on row 2, table 1.

Stocks and flows are a central concept to system dynamics. Stocks represent a state variable (or level) that is to be measured based on inflows and outflows. Stocks can thus be explained mathematically using integrals that aggregate the flows over time as explained in table 1. Flows on the other hand can be explained as rates or time derivatives.

In the example in row 3, table 1, the *sales of HEVs* serves as a flow valve for the accumulation of the stock *HEVs in operation*. The *disposal of HEVs* serves as an outflow valve to that stock. To find the quantity of HEVs in operation over time we simply need to take the integral of a function that describes *sales of HEVs* minus the *disposal of HEVs* over time.

3.1 Stepwise implementation of the Forrester's Methodology

Step 1 – According to Forrester, the first step in the system dynamics methodology is to describe the system of interest based on the goals of the model. In this case, the model aims at studying new vehicle architecture adoption. The elements relevant to the problem encompass relationships that include: the total demand for all cars in the market; the market share of each vehicle architecture considered; the price of gasoline and electricity; the cost of operating a vehicle; government incentives or taxes; the maturity of the electric powertrain technology; retail price premiums of HEVs and BEVs over that of conventional IC engine cars; and network effects that make a car more desirable to the customer.

The selection of these elements stem from asking basic questions of what items are relevant to the adoption of new vehicle architectures and why they are important. The model boundaries are established with the selection of elements and feedback loops. These are created when a set of elements are linked in a cycle. The model is not meant to be all encompassing, but rather a path depiction of variables that help explain the central problem in a cause and effect reasoning chain. At this point the resulting visualization is called a "casual loop diagram" in system dynamics terminology [[8], p.13, p.102].

Step 2 -The second step in the methodology requires converting the system description into level and rate equations. In this step, all elements that show linkages develop a mathematical explanation. Variables that are explained by others within the model are said to be endogenous or internal, whereas variables that are explained by external information or user value inputs are exogenous to the model. In figure 3, exogenous variables are colored in red for easy identification.

Because the number of vehicles of a particular architecture sold is central to the model, three stocks are designated in figure 3: 1. the *number of ICE cars sold*, 2. the *number of HEV/PHEVs sold*[1], and 3. the *number of BEVs sold*. A time horizon of 10 years is assumed for which the simulation time step is set to one year each period. The disposal of cars is left outside the boundaries of this model and is not explicitly shown. At each time step, the simulation calculates the chain of effects that propagate throughout the system based on the mathematical definitions resulting in a year to year increase in vehicles sold. If we assume that the starting year is 2010, then by the end state of the model results in a projection for vehicle sales in year 2020.

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[1] PHEV refers to Plug-in Hybrid Electric Vehicles. In this model, PHEVs are bundled with HEVs together.

Exogenous Variables - red

Endogenous Variables - black

Figure 3 System Dynamics model diagram examining future vehicle architecture adoption scenarios

Step 3 -The simulation step in the systems dynamics methodology is facilitated through the application of mathematical equations encompassing all variables in the model. By looking at the model diagram in figure 3 and comparing with the equations below, it becomes clear that the mathematical equation defining each element is a function of the input relationships to that element. The appendix table presents a listing with all equations and assumptions for all variables in the vehicle architecture adoption model.

This simulation model focuses on the number of vehicle architecture sold each year that add to the installed base of the vehicle architecture type already in operation[2]. The installed base of each vehicle architecture type is defined by the parameter *number sold Architecture i* expressed as a stock by equation 1. Because this parameter represents an accumulating quantity, it can be measured by taking an integral through time. Initial values in the model include ICEs 12 Million, HEV_PHEV 600,000, and BEV 500 – simulating the current new vehicle fleet for sale in the US market in 2010.

$$Number\ Sold\ Architecture_i = \int_{t=0}^{10} Sales\ of\ Architecture_i + initial\ installed\ base_{t=0}$$

$$NumberSoldArchitecturei = \int_{t=0}^{10} SalesofArchitecturei + initialinstalledbase_{t=0} \quad (1)$$

Of particular interest is the definition of vehicle architecture attractiveness, as it is used in assigning market shares in the simulation. The flow into our stock is the sales of vehicle architecture types. The total market demand is set to be a constant number sold per year. Here the market demand is 13 million units per year every year. Equations 2 thru 5 explain the chain of mathematical relationships leading to vehicle architecture sales in the model.

$$Sales\ of\ Architecture\ i = Total\ Demand\ for\ Cars * Market\ Share\ of Architecture\ i \quad (2)$$

$$Market\ Share\ of\ Architecure\ i = \frac{\left[\left(\frac{Attractiveness\ of\ Architecture\ i}{Total\ Attractiveness\ of\ all\ Architectures}\right)+10\left(\frac{Number\ Sold\ Architecture\ i}{Total\ Vehicles}\right)\right]}{11} \quad (3)$$

$$Total\ Attractiveness\ of\ all\ Architectures = \sum_{j=1}^{n} Attractiveness\ of\ Architecture_j \quad (4)$$

$$Total\ Vehicles = \sum_{i=1}^{n} Number\ Sold\ Architecture_i \quad (5)$$

The market share of an architecture type is a weighted function of the attractiveness ratio and the vehicle sold ratio. The vehicle sold ratio in this case is weighted to be 10 times larger than the attractiveness ratio as seen on equation 3. The weighting reflects the fact that manufacturers will produce more of what sells in the market rather than what early adopters find attractive.

Attractiveness represents the customer's affinity for buying the product. This parameter depends on a wide range of variables that are hard to quantify such as emotional aspects of the design, quality perception, selling price, availability, service, features, and so on. In this simplified model, overall attractiveness is a function of the *costs of ownership*, *cost of operation* and the *network effects on attractiveness* as presented in equation 6.

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[2] The term *i* or *j* in the equations that follow refers to Internal Combustion Engine (ICE), HEV or Plug-in HEV (PHEV) and BEV vehicle architectures.

By studying the equations behind the dependencies in figure 3, attractiveness has a positive dynamic feedback loop from the network effects that represent the emotional intangibles of quality, perception and word of mouth reinforcing effects on sales. Attractiveness is balanced by the effects from cost of ownership and operation elements that quantify costs to the customer.

$$\text{Attractiveness of Architecture } i = \frac{\text{Network effects on Attractiveness for Architecture } i}{(\text{Cost of Ownership Attractiveness } i + \text{Cost of Operation Attractiveness } i)} \quad (6)$$

The two variables in the denominator contain information on the selling price and the costs to operate the vehicle. The higher the costs a particular architecture exhibits, the less attractive the architecture type will be in the market, and thus be subject to lower sales. In contrast, the stronger *network effects on attractiveness for Architecture i* are, the more attractive it is in the market.

$$\text{ICE Cost of Ownership Attractiveness} = \frac{((1 + \%\text{CO2 Government Tax or Incentive}) \times \text{Avg.ICE Retail Price})}{\text{Avg . ICE Retail Price}} \quad (7)$$

$$\text{HEV or BEV Cost of Ownership Attractiveness} =$$

$$\frac{((1 + \%\text{CO2 Government Tax or Incentive}) \times \text{Avg.ICE Retail Price} \times \text{Price Premium over ICE})}{\text{Avg. ICE Retail Price}} \quad (8)$$

$$\text{Retail Price Premium over ICE} =$$

$$(1 + (\text{Initial \% Retail Premium over ICE} - \text{Electric Powertrain Maturity} \times \text{Initial \% Retail Premium over ICE})) \quad (9)$$

The cost of ownership equations 7 thru 9 explain costs involved in owning and purchasing a vehicle architecture type. The variable *%*CO_2 *Tax or incentive* can take on a positive (CO_2 Tax) or negative (Government Incentive) value representing here government emissions regulatory activities. A tax makes the cost of ownership higher and the overall attractiveness of the architecture smaller, whereas an incentive has the opposite effect. The model assumes an average selling price of an ICE car at $30,000 representing a traditional mid size passenger car sedan. Exogenous inputs such as the *Avg ICE retail price* can be easily changed to explore other scenarios.

The dimensionless parameter *retail price premium over ICE* represents a means to measure of how much more a PHEV, HEV or BEV retails over a conventional ICE car. This term is a function of the *electric powertrain maturity* to represent the development state of the high voltage battery technology. The estimate of the technological maturity of the battery system is modeled as a constant value between 0 and 1 in equation 9: (A value of 0 = not mature; 1= very mature – meaning an off the shelf component). When the value is set to zero, the full retail premium value is taken, making the cost of ownership larger; whereas a value of one reduces the extra price premium to zero.

The cost of operation equations presented in equations 10 and 11 exhibit a balancing (negative) effect on overall attractiveness of a particular vehicle architecture. Hence, the vehicle architecture that generates the least cost of operation wins out in generating the most attractiveness.

$$Cost\ of\ Operation\ Attractiveness = \frac{Cost\ of\ Operation\ of\ Architecture\ i}{Sum\ of\ Cost\ of\ Operation\ for\ all\ Architectures} \quad (10)$$

$$Cost\ of\ Operation\ of\ Architecture\ i = \frac{Price\ of\ Fuel\ (or\ Electricity)}{Average\ Fuel\ (or\ Electric)\ Consumption\ of\ Architecture\ i} \quad (11)$$

The *cost of operation attractiveness* of a particular architecture is defined as a ratio to all other architectures. This definition allows assigning the highest value towards cost of operation to the architecture that carries the highest operating cost. The actual cost of operation is a function of the price of fuel, or electricity in the case of BEVs, and the energy consumption.

The prices are exogenous variables to the model to allow for the creation of various price scenarios. The price of gasoline used in the simulation is based on the US Energy Information Administration (EIA) projections from 2010 to 2030 [9]. The price of electricity in the model is left as constant at \$0.11/kWh as the EIA projects little change in its pricing over the next 10 years. Both of these exogenous variables can be further studied for sensitivity.

The *network effects on attractiveness* in turn is constructed to capture the positive influence a larger installed base of a particular architecture type has on the attractiveness for further sales of that type.

$$Network\ Effects\ on\ Attractiveness = e^{\left[(Sensitivity\ to\ network\ effects) * \frac{Number\ Sold\ of\ Architecture\ i}{Threshold\ for\ Network\ Effects}\right]} \quad (12)$$

This relationship is described by means of an exponential function as seen on equation 12.

This exponential function has three terms that control the positive feedback on the sales of more vehicles for a particular architecture type: a sensitivity constant, the number of vehicle sold (our stock) and a threshold constant. The parameter *sensitivity to network effects* controls the strength of the exponential growth effect of product attractiveness. The threshold is essentially a scaling factor that represents the size of the installed based above which network effects become important.

The use of an exponential curve to describe network effects is a plausible model. For new technologies entering a market this is similar to the so called “snowball” dynamic where the sales of a new technology grow exponentially after enough customers have adopted the new market standard. Once the technology dominates to the point all customers have the product network effects on sales reduce.

As an example, consider the relatively unknown BEV architecture. The sensitivity parameter is set to 4, the threshold to 5 million vehicles and the initial number of vehicles sold initially is assumed to be only 500 cars. Before the number of BEVs sold reaches the 5 million vehicle mark, the network effects are relatively weak displaying almost linear growth (initially set at $e^{4*(500/5000000)}$). Once the number of BEVs sold reach the threshold of 5 million BEVs sold, the exponential function simply becomes e^5. Finally, once the number sold surpasses 5 million units sold network effects become much stronger as the right side term in the exponential function becomes a multiplier allowing sales to expand at a powerful increasing rate year to year.

Table 2 Simulation results based on initial conditions and equations described in the appendix table

Time (year)	Number of ICEs Sold (in Millions)	Number of HEV_PHEVs Sold (in Millions)	Number of BEVs Sold (in Millions)	Total Vehicles (in Millions)	Market Share ICE	Market Share HEV_PHEV	Market Share BEV	Attractiveness of ICE	Attractiveness of BEVs	Attractiveness of HEV_PHEV
0	12.5	0.6	0.0005	13.1	0.90	0.07	0.02	0.8	0.5	0.7
1	24.2	1.6	0.3	26.1	0.88	0.09	0.03	1.0	0.7	1.0
2	35.7	2.7	0.7	39.1	0.86	0.10	0.04	1.4	0.9	1.6
3	46.9	4.0	1.2	52.1	0.85	0.11	0.04	1.8	1.4	2.5
4	57.9	5.4	1.8	65.1	0.83	0.12	0.05	2.4	2.2	4.3
5	68.7	7.0	2.4	78.1	0.82	0.13	0.05	3.1	3.7	7.7
6	79.3	8.7	3.1	91.1	0.81	0.14	0.05	4.1	6.3	14.4
7	89.8	10.5	3.8	104.1	0.80	0.15	0.06	5.3	11.0	28.4
8	100.2	12.4	4.5	117.1	0.78	0.16	0.06	6.8	19.6	58.8
9	110.4	14.5	5.2	130.1	0.78	0.17	0.06	8.8	35.1	127.5
10	120.5	16.7	6.0	143.1	0.77	0.18	0.05	11.3	62.4	290.3

Steps 4 and 5 – These steps in the system dynamics methodology require interpretation of the simulation results that lead to a deeper understanding of how variables described in the model represent reality. This understanding must then be communicated to others in order to educate and debate potential policy or strategic actions to be undertaken.

4 SIMULATION RESULTS

The simulation was run using the Vensim PLE Plus® System Dynamics software using the equations and initial conditions described in the appendix table. Selected model results are displayed in table 2. Initially, the number of new vehicles sold is set to 13.1 million units, set to grow annually at a rate of 13 million new cars – roughly the size of the US light duty vehicle market. The numbers of vehicle sold accumulate through the 10 year period to 143 million vehicles.

Initially, the ICE architecture has a dominant position in sales and slowly looses market share to the HEVs, PHEVs and BEVs as they become more attractive. The losses in market share are due to the exponential explosion in attractiveness the HEVs and BEVs experience once the threshold for network effects is achieved (8 million for HEVs/PHEVs and 5 million for BEVs). At the end of ten years, the percentages for each architecture type is as follows: 84% ICE cars sold; 12% HEV and PHEV cars sold and 4% BEV cars sold. The final year market shares result in 77% ICE cars, 18% for HEV cars and 5% for BEVs. These results are comparable with industry projections presented in figure 1.

SENSITIVITY STUDY ON FUEL PRICE FLUCTUATION

The simulation permits the study of sensitivities between variables that allow for insights on how changes propagate in the model. For example, figure 4 displays the results of the simulation run 200 times allowing the price of fuel to randomly vary between $2 per gallon and $9 per gallon (roughly 0.42 Euros/liter and 1.87 Euros/liter respectively) using a standard normal distribution. The results allow for exploration on how sensitive market share values are using the aid of confidence intervals.

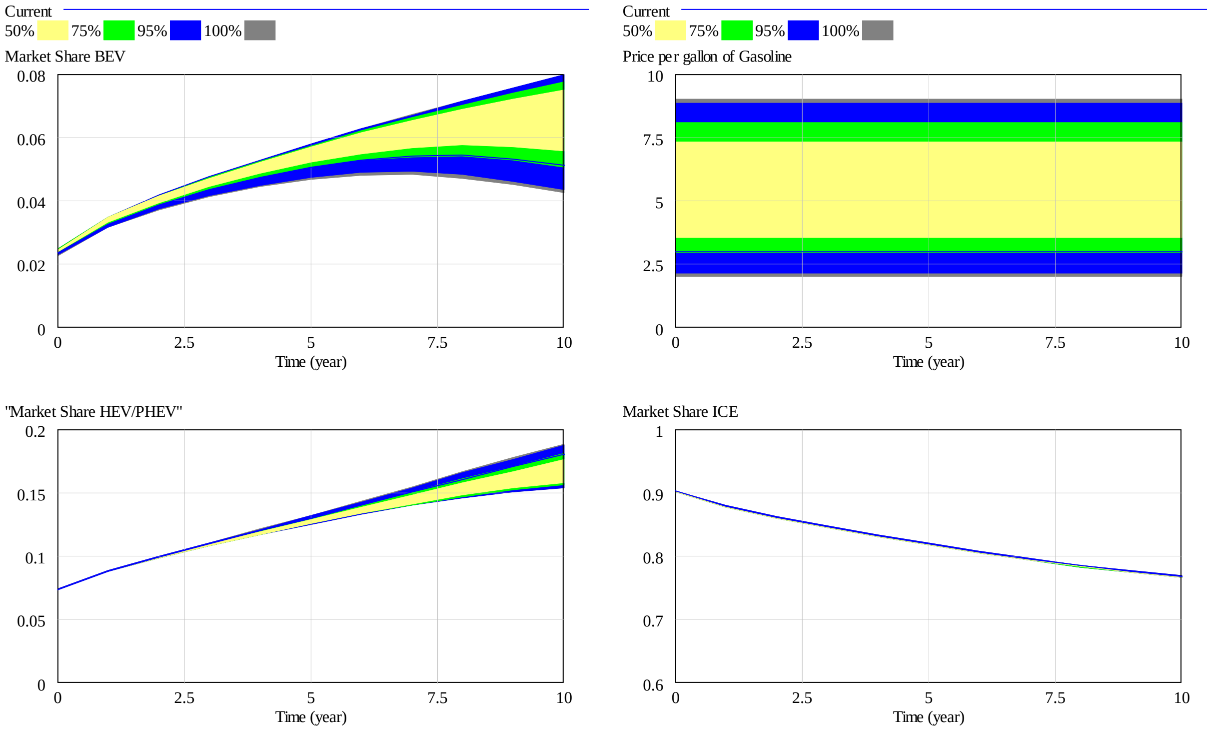

Figure 4 Market share confidence intervals resulting from 200 simulations varying price of gasoline as a random variable between $2 and $9 per gallon (roughly 0.42 Euros/liter and 1.87 Euro/liter)

From figure 4, it is interesting to note that the market share of ICEs is not sensitive to changes in fuel prices - as might be thought of originally. In contrast, changes in fuel prices propagate much more markedly in the market share for HEVs and BEVs evidenced by a broader distribution.

A closer examination reveals that the variance for the BEV architecture grows exponentially larger after the 3rd year and for the HEVs after the 5th year. The reason for these results is that the price of fuel affects the *cost of operation* metrics, which then in turn have an effect on the attractiveness of the vehicle architecture types. Variations in attractiveness for the two incumbent architectures (the BEV and HEVs) are more pronounced as the number of vehicle sold reaches the threshold for network effects as seen in table 2. The attractiveness metrics of ICEs are less affected because the sensitivity to network effects is set to be much lower than the new vehicle architectures. This assumption relates to the fact that the ICE car is the current dominant architecture and network effects have been satisfied as almost every user today already owns an IC engine car.

CONCLUDING REMARKS

This paper shows the implementation of a proposed modeling methodology to the applied example of new vehicle architecture adoption. The utility of the model presented lies in its ability to link many factors relevant to the early design of new vehicle architectures that are generally very difficult to assess during the design process. Because each link is mathematically related, change propagation based on changes to input variables is simple to follow.

Change propagation within the modeled elements has clear policy implications for firms looking to use positive feedbacks to their advantage. One example is in the use of network effects to gain market share. The model shows that network effects will be relatively weak during the introduction of new vehicle architectures where no prior standards have been established. The initial market will tend to stay true to the known and proven products of the installed base. As a result, the first movers in the new vehicle markets will likely accrue small market shares in exchange of high costs of innovation and development.

As the new product market develops, only a small window of time exists for second market movers to offer an improved version of the new vehicle architecture to capture the new market share as it becomes available. The time window to be successful as a second mover is very limited due to the fact that market share growth follows seemingly linear growth that quickly develops to exponential propagation of the new architecture offering. Hence, the second mover strategy needs to develop an improved product at the right time. In the automotive industry this “right time” must be backwards planned to allow for 3-6 years development time [10]. By the time the new market develops, it is usually too late to start the innovation and development process for a second mover in the market.

REFERENCES

[1] Frost, L., Renault, Nissan to Form Car battery Venture with French State. *Bloomberg.com* (Bloomberg, New York, 2009).

[2] Book, M., Groll, M., Mosquet, X., Rizoulis, D. and Sticher, G., The Comeback of the Electric Car? How Real, How Soon, and What Must Happen Next. (Boston Consulting Group, Boston, MA, 2009).

[3] Klink, G.K., Stephan Rings,Thomas. Sparsam, sauber, elektrisch? Das Rennen um den Antrieb der Zukunft: Die Automobilindustrie auf dem Weg zu Nachhaltigkeit und Elektrifizierung. *AT Kearney*, 2009.

[4] Wertel, K.G., Wunder dauern etwas laenger. *Handelsblatt*, 2008(September), pp24.

[5] Global Insight. Global Powertrain Analysis and Forecasting. *Powertrain and Forecasting Brochure* (IHS Global Insight, 2009).

[6] ACEA. European Automobile Manufacturer's Association (ACEA): Frequently Asked Questions on CO2 Emisions [online]. 2009. Available from: http://www.acea.be/index.php/collection/co2_emissions_faq_on_co2/#Q5 [Accessed on 30 October 2009]

[7] Forrester, J.W., System dynamics, systems thinking, and soft OR. *System Dynamics Review*, 1994, Vol. 10,(No. 2).

[8] Sterman, J.D., *Business dynamics: Systems thinking and modeling for a complex world with CD-ROM*. (Irwin/McGraw-Hill, 2000).

[9] EIA. US Energy Information Agency, U.S. Retail Gasoline Prices [online]. 2009. Available from: http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_home_page.html [Accessed on 16 December 2009]

[10] Fricke, E. and Schulz, A.P., Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. *Syst. Eng.*, 2005, Vol. 8(No. 4), pp308.301-308.302.

APPENDIX: SIMULATION MODEL EQUATIONS

Type of Element	Model Element(s)	Mathematical Equations(s) / Input Values	Units	Comment
Stocks - Endogenous	Number of ICEs Sold, Number of HEV_PHEVs Sold, Number of BEVs Sold	Number Sold = Integral (Sales) + initial value	Units	Stocks are accumulating quantities that can be measured as a level at a particular point in time . This model focuses on the number of vehicle architecture sold each year that add to the installed base of vehicle architecture types already in operation. Initial values in the model include ICEs 12 Million, HEV_PHEV 600,000, and BEV 500.
Flows - Endogenous	Sales of ICEs, Sales of HEVs_PHEVs Sold, Sales of BEVs Sold	Sales = Market Share * Total Demand for Cars	Units/year	To simplify the model we assume only inflows are considered to our stocks. These flows are the sales of vehicle architecture types.
Exogenous	Total Demand for Cars	Estimate: 13 million; Minimum: 0; Maximum: 5; Increment: 0.01	Units	The total market demand can be set to be a constant number sold per year or modeled to increment yearly. In this simplified case it is assumed the market demand is 13 million units per year every year.
Endogenous	Market Share ICE, Market Share HEV_PHEV, Market Share BEV	Market Share = Attractiveness / Total attractiveness of all Architectures	Dmnl	Market share is defined as the percentage of a car architecture's attractiveness to the total attractiveness. The sum of all market shares must equal 100%.
Endogenous	Attractiveness of ICE, Attractiveness of HEV_PHEV, Attractiveness of BEV	Attractiveness = Network Effects on Attractiveness / (Cost of Operation Attractiveness * Cost of Ownership Attractiveness)	Dmnl	Attractiveness represents the customers affinity for buying the product. The equation has a positive dynamic feedback from network effects and balancing effect from cost of ownership and operation elements
Endogenous	Network Effects on Attractiveness ICE, Network Effects on HEV_PHEV Attractiveness, Network Effects on BEV Attractiveness	Network Effects on Attractiveness = EXP(Sensitivity of Attractiveness to Network Effects*(Number Sold/ Threshold for Network Effects)	Dmnl	Network effects rise exponentially as the installed base grows relative to the threshold where network effects become important. The sensitivity parameter controls the strength of the effect.
Exogenous	ICE Sensitivity of Attractiveness to Network Effects	Estimate: 0.001; Minimum: 0; Maximum: 5; Increment: 0.01	Dmnl	The sensitivity of attractiveness represents how big the network effect will be after the threshold of cars needed in the market to generate a positive influence on sales is achieved. Because the ICE car has dominance of the market the network effects are set to be minimally sensitive. New vehicle architectures are set to have much stronger network effects.
Exogenous	HEV_PHEV Sensitivity of Attractiveness to Network Effects	Estimate: 0.1; Minimum: 0; Maximum: 5; Increment: 0.01	Dmnl	
Exogenous	BEV Sensitivity of Attractiveness to Network Effects	Estimate: 0.1; Minimum: 0; Maximum: 5; Increment: 0.01	Dmnl	
Exogenous	ICE Threshold for Network Effects	Estimate: 13 Million	units	The threshold constant is a scaling factor that represents the number of units needed in operation after which network effects take on a strong positive feedback dynamic influence.
Exogenous	HEV_PHEV Threshold for Network Effects	Estimate: 3 Million	units	
Exogenous	BEV Threshold for Network Effects	Estimate: 10 Million	units	
Endogenous	ICE Cost of Ownership Attractiveness	ICE Cost of Ownership Attractiveness = ((1+%CO2 Government Tax or Incentive)*Avg. ICE Retail Price)/ Avg. ICE Retail Price	Dmnl	The cost of ownership equations serve as a balancing effect to the attractiveness of a vehicle architecture. The variable "%CO2 Tax or incentive" can take on a positive (CO2 Tax) or negative (Incentive) value representing government emissions regulatory activities. A tax makes the cost of ownership larger and the overall attractiveness of the architecture smaller, whereas an incentive has the opposite effect. The model assumes an average price of $30000 representing a mid size passenger car sedan. The exogenous inputs to the model can be easily changed to explore other scenarios.
Endogenous	HEV_PHEV Cost of Ownership Attractiveness	HEV (PHEV) Cost of Ownership Attractiveness = ((1+%CO2 Government Tax or Incentive)*Avg. ICE Retail Price* HEV_PHEV Retail Price Premium over ICE)/Avg. ICE Retail Price	Dmnl	
Endogenous	BEV Cost of Ownership Attractiveness	BEV Cost of Ownership Attractiveness = ((1+%CO2 Government Tax or Incentive)*Avg. ICE Retail Price* BEV Retail Price Premium over ICE)/Avg. ICE Retail Price	Dmnl	
Exogenous	Avg. ICE Retail Price	Estimate: 30000 ; Minimum: 5000 ; Maximum: 150000 ; Increment: 1000	$	
Exogenous	%CO2 Government Tax or incentive	Estimate: 0.2; Minimum: -0.9; Maximum: 0.9; Increment: 0.1	Dmnl	
Endogenous	HEV_PHEV Retail Price Premium over ICE	HEV_PHEV Retail Price Premium over ICE = (1+(Initial HEV % Retail Premium over ICE - (Electric Powertrain Technology Maturity*Initial HEV % Retail Premium over ICE)))	Dmnl	This dimensionless value represents a means to measure of how much more a PHEV, HEV or BEV retails over a conventional IC Engine car, that is a function of the maturity of the electric powertrain technology to represent the high voltage Battery development. The estimate of the technological maturity of HV Batteries is as follows: (A value of 0 = not mature; 1= off the shelf component). When the value is zero the full premium value is taken making the cost of ownership larger, whereas a value of one makes reduces the extra price premium to zero.
Endogenous	BEV Retail Price Premium over ICE	BEV Retail Price Premium over ICE = (1+(Initial BEV % Retail Premium over ICE - (Electric Powertrain Technology Maturity*Initial BEV % Retail Premium over ICE)))	Dmnl	
Exogenous	Initial HEV % Retail Premium over ICE	Estimate: 0.35; Minimum: 0.05; Maximum: 0.55; Increment: 0.1	Dmnl	
Exogenous	Initial BEV % Retail Premium over ICE	Estimate: 0.7; Minimum: 0.1; Maximum: 1.5; Increment: 0.1	Dmnl	
Exogenous	Electric Power Train Maturity	Estimate: 0.1; Minimum: 0; Maximum: 1; Increment: 0.1	Dmnl	
Endogenous	ICE Cost of Operation Attractiveness, HEV_PHEV Cost of Operation Attractiveness, BEV Cost of Operation Attractiveness	Cost of Operation Attractiveness = Cost of Operation / Cost of Operation Sum	Dmnl	The cost of operation equations have a balancing (negative) effect on overall attractiveness of a particular vehicle architecture type. The vehicle architecture that generates the least cost wins out in generating the most attractiveness. The model uses several assumptions in its exogenous variables that help build various scenarios. The price of gasoline and electricity are based on the US Energy Information Administration (EIA) projections from 2010 to 2030.
Endogenous	ICE Cost of Operation	ICE Cost of Operation = Price per gallon of Gasoline/ Average Gas Mileage of ICE	$/miles	
Endogenous	HEV_PHEV Cost of Operation	HEV_PHEV Cost of Operation = Price per gallon of Gasoline / Average Gas Mileage of HEV	$/miles	
Exogenous	BEV Cost of Operation	BEV Cost of Operation = Price per kWh/ Average Mileage per kWh of BEV	$/miles	
Endogenous	Cost of Operation Sum	Cost of Operation Sum = ICE Cost of Operation + BEV Cost of Operation + HEV_PHEV Cost of Operation	$/miles	
Exogenous	Price Per Gallon of Gasoline	$2.99 in year one increasing to $5.63 in year 20 according to EIA	$/gal	
Exogenous	Average Gas Mileage of ICE	Estimate: 20; Minimum: 10; Maximum: 100; Increment: 5	miles/gal	
Exogenous	Average Gas Mileage of HEV	Estimate: 30; Minimum: 10; Maximum: 100; Increment: 5	miles/gal	
Exogenous	Price Per kWh	$0.13 per kWh	$/kWh	
Exogenous	Average Mileage per kWh of BEV	Estimate: 4; Minimum: 2; Maximum: 6; Increment: 0.05	miles/kWh	