Evaluation of Hybrid Vehicle Business Strategy

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1 Abstract

This report analyzes whether a car manufacturer should design its next-generation hybrid vehicles around lithium-ion (li-ion) batteries, or whether it should continue to use nickel-metal hydride batteries. The analysis uses a simple demand-side model to equate the net present value of lifetime fuel savings to sales volume. The lithium-ion battery shows greater potential to improve and, by allowing for limited electric range, can deliver a higher value proposition to the consumer in the event of high gas prices; the NiMH battery is cheaper.

Detailed decision analysis of the two different options shows that:

1.) At expected rates of improvement (< 2.5% cost reduction/yr),
2.) Moderate fuel price scenarios (<$4.00 gallon), and
3.) Zero or low carbon tax (<$0.40/gallon),

The NiMH battery remains the better choice. Under high growth, high gas prices, or with a carbon tax in effect, the li-ion battery can deliver improved sales volumes. These results are robust across several different evaluation methods. On balance, it appears that adopting the flexible option is premature at this point in time.

2 Introduction

2.1 Project Overview

This study will evaluate two different business strategies for a hybrid-electric vehicle (HEV) platform that will enter the US market in 2012. The first strategy uses Nickel-Metal Hydride (NiMH) batteries as the centerpiece of a fixed platform. This fixed platform offers a fixed improvement in fuel economy.

The second strategy uses a flexible platform enabled by a transition to lithium-ion (LI) batteries. The higher energy density of the lithium-ion battery gives the flexibility to adjust the vehicle's fuel efficiency across a wide range of levels according to respond to current market conditions: the flexible platform can implement a baseline configuration that gives similar performance to that of the NiMH platform; by using a bigger battery pack, it can add limited electric range (in a plug-in hybrid configuration); or it can use a smaller battery pack to implement a less-hybridized (mild hybrid) configuration.

While the LI-based platform offers improved ability to respond to current market conditions, this flexibility increases the vehicle purchase price. The higher cost arises from several sources: NiMH batteries are a little bit cheaper; there is less risk associated with the battery pack warranty; and the flexible platform will have higher vehicle integration costs (due to the multi-purpose platform). These costs will all be internalized in the vehicle's purchase price.

The principal variable under the division's control is the vehicle fuel economy. Within the context of this study, the fuel economy is treated as a function of the size of the vehicle's battery pack (an aggregate combination of battery energy and power). This relationship between fuel economy and battery size is obtainable using ADVISOR, a vehicle modeling software package.

The goal of the hybrid vehicle division is to maximize profits from their HEV platform. To compute profits from the HEV platform, the following assumptions are made:

1.) Sales volume is a function of the vehicle's net present value (NPV) compared to a conventional powertrain:

$$\mathbf{NPV = PV_{Lifetime\ Fuel\ Savings} - Price\ Premium}$$

2.) Initial analysis assumes that all vehicle configurations are equally profitable on a per-vehicle basis ($2000/vehicle). Hence, profits are a fixed multiplier of sales:

$$\mathbf{Profit = (Total\ Sales)(\$2000)}$$

3.) Subsequent analysis will vary the assumption that different vehicles are equally profitable. In particular, we will assume that government incentives cause profit to scale with lifetime fuel savings.

$$\mathbf{Profit = (Total\ Sales)(\$2000 + (Fuel\ Saved)(Internalized\ Value\ of\ Fuel\ Saved))}$$

The two options (flexible and inflexible) will be evaluated using several different decision tools, including a decision tree, lattice analysis, and a Monte Carlo simulation.

It is assumed that the vehicle platform under development has an 18 year lifetime from its market entry in 2012. Under the flexible strategy, build decisions have a 3-yr life. That is, every 3 years, the manufacturing division builds the optimum vehicle based on forecasts for the next 3 years. Under the fixed strategy, the same build option is used throughout the project lifetime.

2.2 Background on Hybrid-Electric Vehicles

Since their market introduction in 1998, hybrid-electric vehicles (HEV) have shown a steady and dramatic increase in market-share. However, it is important to recognize that, while growth rates have been dramatic, in absolute terms, hybrids still represent a very small fraction of new vehicle sales – on the order of 1% in model year 2005. It is unclear whether this growth will continue, or whether the hybrid represents a niche market that is nearing saturation [HybridCars.com].

It is also not clear what sort of hybrid vehicle designs will prove most popular with consumers. The principal variable in this dimension is the vehicle's fuel consumption. The most successful HEV to date has been the Toyota Prius; the Prius uses a relatively robust battery pack and control strategy to deliver improvements in fuel economy of up to 30-35% over other equivalent vehicles. However, a significant fraction of these benefits (~20%) can be accrued using a smaller (read: less expensive) battery and simpler vehicle architecture. It is conceivable that the market could evolve towards these lower priced "mild hybrid" configurations. [EPAa]

On the other end of the spectrum, consumer demand might also push the market towards plug-in hybrid vehicles (PHEVs). Present-day hybrids derive all of their energy from gasoline; however, advances in battery technology, coupled with mounting concern over reliance on foreign oil have piqued interest in the PHEV. A plug-in hybrid is a hybrid vehicle endowed with a modest electric range and the ability to recharge its battery from the electric grid. This vehicle configuration allows the user to drive in an all-electric mode during short trips (which comprise the bulk of day-to-day driving), while allowing the flexibility to travel longer distances once the battery charge has depleted. A PHEV could potentially offer electric-vehicle type benefits at a modest price increase over the HEV. Such a vehicle would use a platform similar to that of the Toyota Prius.

The major enabling technology in hybrid vehicles is the battery. To a first-order approximation, the incremental cost of an HEV over an equivalent gasoline-powered vehicle is a function of the battery cost. (Increased costs associated with adding a motor and power electronics are typically offset by savings associated with a downsized engine). Present-day hybrids use nickel-metal hydride (NiMH) batteries. These offer only a moderate level of performance (defined by specific power (W/kg) and specific weight (W-hr/kg), but excellent durability and moderate cost.

There is a widespread feeling among experts that lithium-ion (Li-ion) batteries will become the dominant chemistry in the HEV market at some point in the future. Because a lithium-ion battery has better power and energy density, they can deliver higher performance, smaller package sizes, and enable the development of plug-in hybrid vehicles. The factors preventing the lithium-ion battery from entering the market are its durability and its higher cost. The durability issue is particularly important, as manufacturers will need to warranty HEV batteries for 10-15 years [Anderman].

2.3 Model Details

Figure 1 shows a conceptual diagram of the system model used to assess vehicle demand. **Error! Reference source not found.** lists the exogenous and endogenous variables that will influence the model outputs. The endogenous variables encapsulate those factors that may be varied by the manufacturing division.

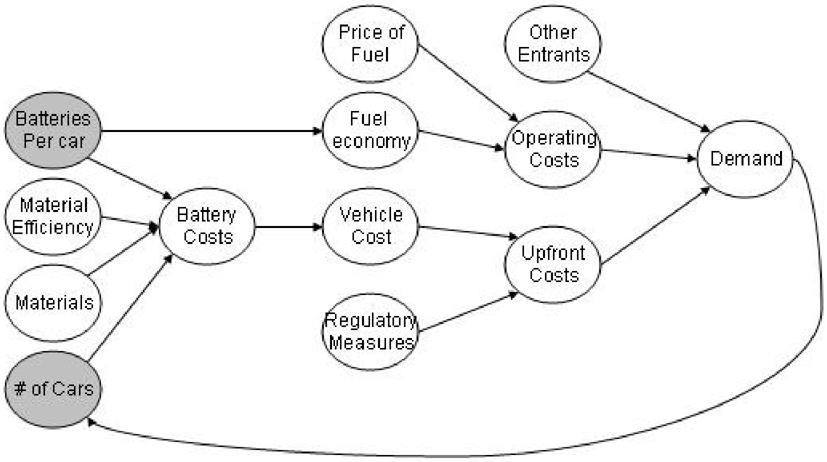

Figure 1: Conceptual model of the proposed system. Shaded circles represent the system's independent variables. ***Note: the production volume (# of cars) is not an independent variable. This is a mistake.***

Exogenous Variables	Endogenous Variables
▪ Fuel price ▪ Discount rate ▪ Consumer demand elasticity ▪ Commodity material prices ▪ Improved Technology ▪ Regulatory Environment	▪ # of batteries/vehicle ▪ Type of battery (NiMH or Li-Ion)

Table 1: Summary of design variables and external factors that influence the model's outcomes

A vehicle's upfront incremental cost is a function of the vehicle battery pack and of the regulatory structure in place. Currently, the "regulatory structure" essentially consists of subsidies for purchasing HEVs, and the CAFÉ standards, according to which manufacturers must meet an average sales-weighted fuel economy level.

The price premium is a function of several factors [EPRI, Appendix C]:

1.) Power electronics + tertiary systems. This is approximately constant at $1000 for all of the flexible options.
2.) Battery cost: This is primarily a function of the battery energy, but there are economies associated with the lower power battery packs required for the more hybridized systems. This will vary over the life of the project (as technology improves, economies of scale are achieved, etc). The baseline assumptions use the projected cost at the project midpoint. Overall, the range in battery cost is $550-$900/kWh.
3.) Onboard charger. This adds $500 to the plug-in options, but is not necessary for the other vehicles.

The vehicle's operating cost is a function of fuel prices and vehicle fuel efficiency, as well as vehicle lifetime, yearly mileage, and discount rate. This valuation will assume fixed vehicle lifetime, mileage, and discount rate. Fuel efficiency is a function of which vehicle configuration is chosen; and fuel price is a key uncertainty that will be modeled.

It is assumed that demand for a vehicle conforms to the following function:

1.) Demand is normally distributed around a mean NPV of $1000 with a standard deviation of $1200.
2.) The maximum sales volume is 1 million vehicles

The relevant demand curves using these assumptions are shown in Figure 2 and Figure 3 (below). The logic for choosing this model is discussed in Section 3.1. Note that, because lifetime fuel savings does not necessarily pay for the higher upfront cost of a hybrid vehicle, the NPV may be negative or positive.

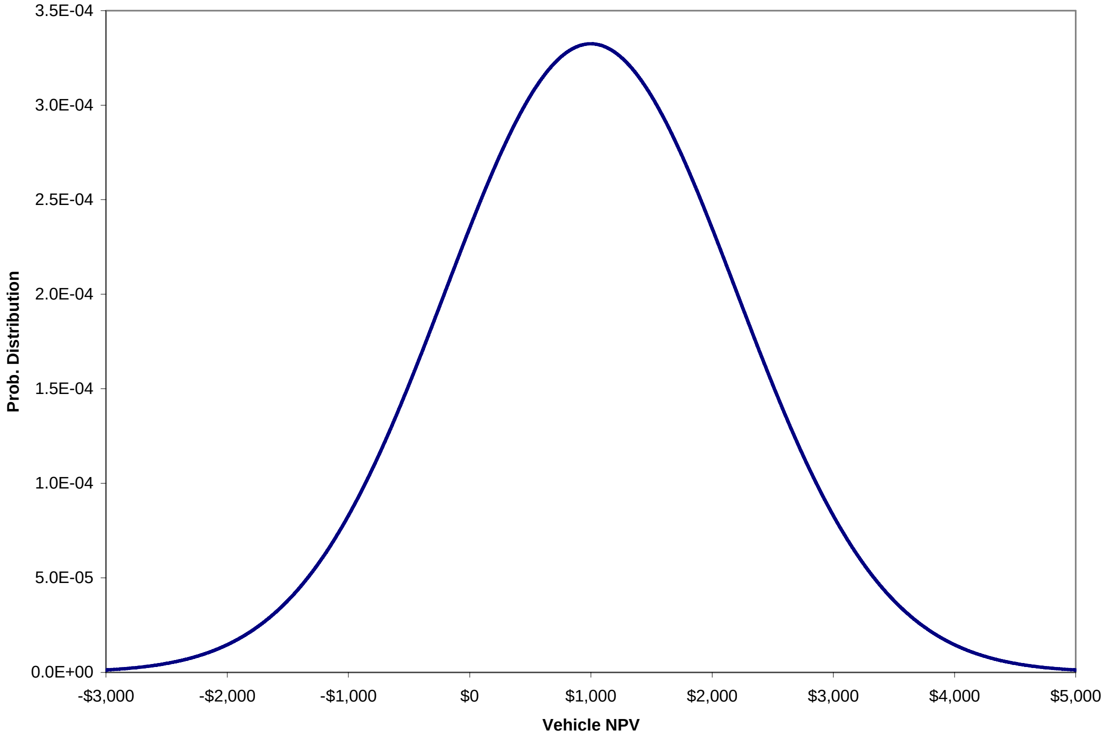

Figure 2: Customer preference for vehicle NPV.

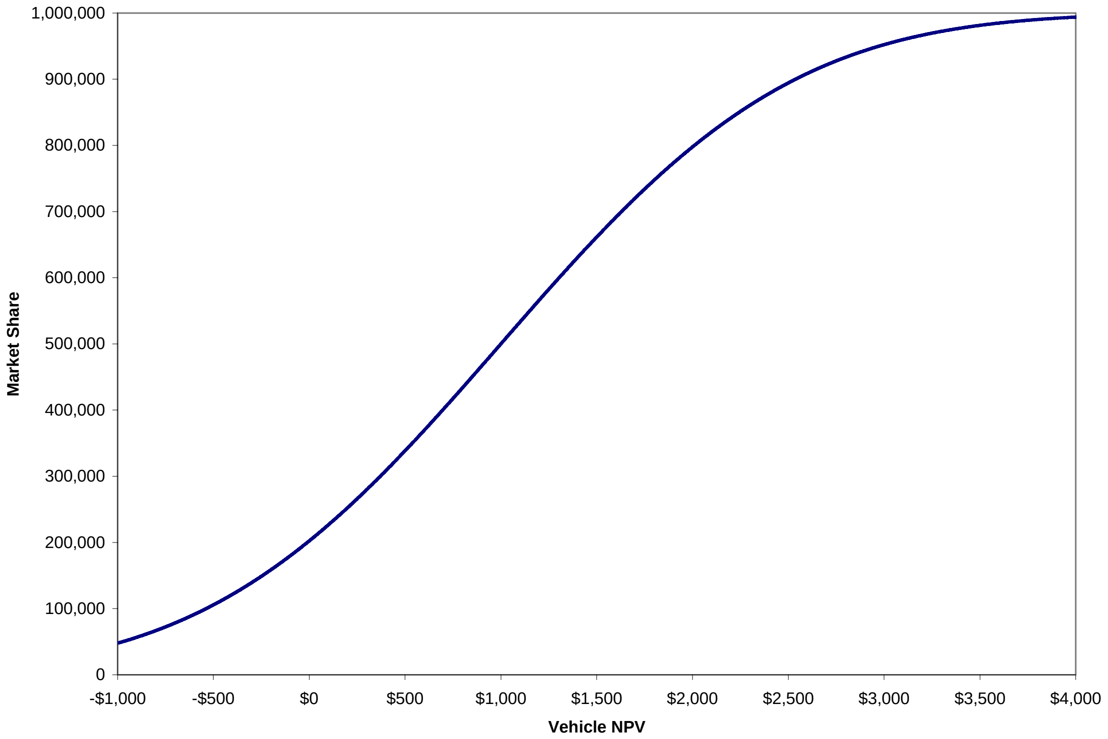

Figure 3: Cumulative market share garnered by increasing vehicle NPV

In addition to the demand curve, it is necessary to make a number of initial assumptions about vehicle characteristics and usage patterns. These assumptions are summarized in Table 6. Except for gas price, these values are fixed inputs to the sales model. Rigorous justification for the selected values is not offered; rather, they represent middle-of-the-road numbers that are commonly used in the industry. To the extent possible, a justification is offered for the assumption in the right-most column.

Parameter	**Assumed Val.**		**Justification**
Consumer Discount Rate	12%		
Gas Price (initial)	$2.75	*per Gallon*	Assumption
Electricity Price (fixed)	$0.09	*per kWh*	~Nat’l Avg (EIAb)
Vehicle Lifetime	15	*Years*	Assumption
Vehicle Miles Traveled (VMT)	15,000	*per Year*	Std. EPA Assumption
Baseline (Conventional) Vehicle Fuel Use	30	*MPG*	ADVISOR Model
Energy Use, Electric Mode	0.2	*kWh/mi*	ADVISOR Model
Mean NPV, demand model	$1000		Assumption
Standard Deviation, demand model	$1200		Assumption
Max. Sales	1,000,000	*Vehicles*	Assumption
Profit	$2,000	*per Vehicle*	Assumption

Table 2: Baseline Cross-cutting assumptions

Vehicle Configuration	Fuel Cons. Improvement	% of Mi Electric	MPG	Gallons Saved/Yr	kWh/Yr	Battery (kWh)	Price Premium
Full Hybrid, NiMH	25%	0%	40.0	125	0	2	$2,500
Mild Hybrid, LI	15%	0%	36.6	90	0	1	$2,500
Full Hybrid, LI	25%	0%	40.0	125	0	2	$3,300
PHEV-10, LI	25%	20%	50.0	200	600	3	$5,000
PHEV-20, LI	25%	30%	67.1	238	900	5.5	$6,000

Table 3: Vehicle Configuration Details. Specific values are calculated from previously specified assumptions.

Table 3 (above) shows specific assumptions about the vehicle characteristics under consideration. The price premiums represent estimates of the vehicle cost at the project midpoint (i.e., year 2020). The bottom four vehicle configurations ("Mild Hybrid", "Full Hybrid", "PHEV-10", and "PHEV-20", shaded in gray) comprise the options available if the flexible option is pursued. The inflexible option allows only the full-hybrid NiMH configuration. The mild-hybrid and full-hybrid both rely on gasoline for all of the motive energy; amongst these vehicles, a larger battery pack and more sophisticated controls allow for higher fuel economy. The two plug-in options (PHEV-10 and PHEV-20) offer increasing amounts of electric range – the PHEV-10 gives 10 miles of electric range, and PHEV-20 gives 20 miles. Increasing a vehicle's electric range displaces an increasing amount of gasoline, but shows diminishing returns (hence, the first 10 miles of electric range account for about 20% of vehicle miles traveled (VMT), while the second 10 miles account for only an additional 10%). This relationship between electric range and fraction of vehicle miles traveled (VMT) has been estimated in the literature, and is shown in Figure 4 [SAE].

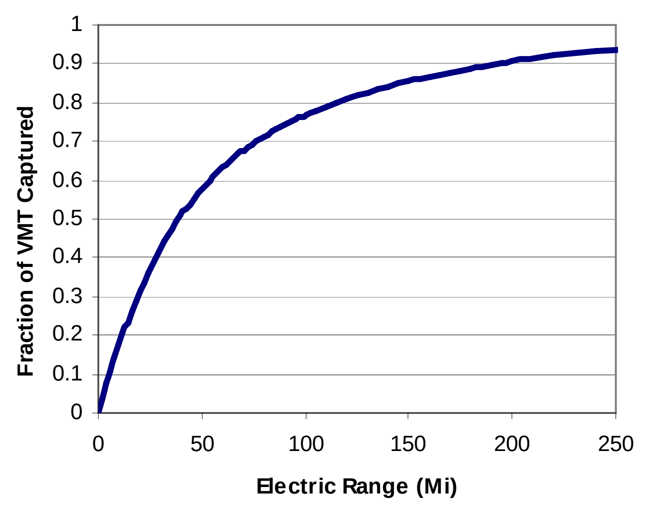

Figure 4: Relationship between electric range and vehicle miles traveled (VMT).

3 Overview of Uncertainties

The market-competitiveness of a fuel efficient vehicle is influenced by several sources of uncertainty. Major factors include: cost of fuel; improvements in enabling technologies; consumer demand elasticity for fuel efficient, environmentally-friendly cars; and government incentives (such as a carbon tax).

The nature of each of these uncertainties is discussed below. However, due to the complexity and scope of these uncertainties, a number of simplifying assumptions are made. The bulk of the analysis will focus on the sensitivity of the optimum business strategy to volatility in the price of fuel under different static assumptions for purchase price. Although it does not reflect reality, the model uses a simple demand curve equating fuel efficiency to vehicle sales.

3.1 Demand Elasticity

Historically, consumers in the United States have shown little interest in fuel efficient vehicles. To the extent that people make these decisions in economic terms, they tend to demand very short payback periods (2-3 years). In addition, it is not even clear that consumers purchase a vehicle with any concept of how much they spend on fuel (in economic terms, consumer behavior is not "rational" in this context).

However, there are signs of a behavioral shift. This consumer apathy towards fuel economy must be viewed against the backdrop of the low gas prices that have been prevalent in the US over the last 20 years. More recently, there have been signs that consumer behavior is changing in the presence of higher gas prices and environmental concerns. (The recent level of angst over gas prices was not justified as a consequence of the relative increases spurring the angst…)

There is no clear picture of how consumer demand changes with higher fuel prices, although there are signs that sustained prices over $3.00/gallon can certainly lead to a paradigm shift. As described previously, this analysis will treat demand elasticity, and hence sales volume, as a function of the vehicle's NPV. In particular:

3.) Demand for a given vehicle is normally distributed around a mean NPV of $1000 with a standard deviation of $1200.
4.) The maximum sales volume is 1 million vehicles.

This demand model attempts to link purchase decisions to NPV, but account for differences between different consumers. This assumes a far more rational (economic) framework for consumer car purchases than has been the case historically.

3.2 Gas Price

Because fuel prices affect the value proposition of a hybrid vehicle to a consumer, the price of gasoline will heavily influence demand for hybrid vehicles and dictate the optimum level of fuel efficiency to be built into future production.

Fuel prices tend to be very volatile: they vary according to political climate, variations in demand, weather, time of year, tax policy, and a host of other factors to numerous to list here. In addition, it is not clear whether the long-run price of fuel will remain relatively constant, go up, or go down. The EIA gives both short- and long- term projections for fuel prices, but these projections have a poor track record (and also tend to damp out the historical volatility in price). In absolute terms, gas prices enjoyed a period of relative stability through the 1980s and early- to mid- 1990s. Since that time, prices have varied dramatically and generally trended upwards. These trends are illustrated in Figure 6 and Figure 5.

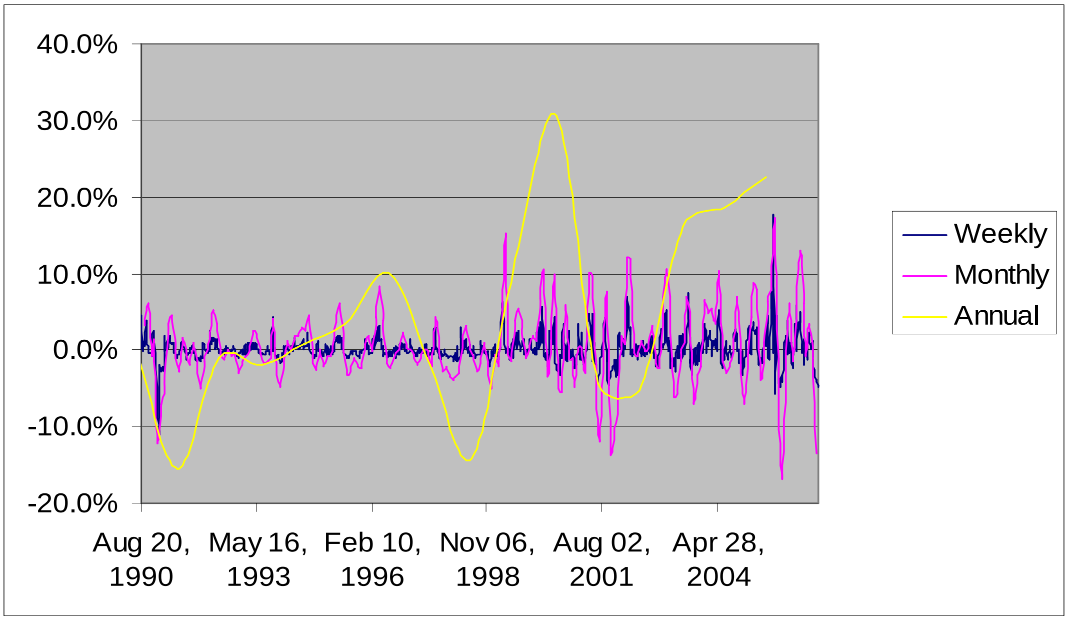

Figure 5: Weekly, monthly, and yearly volatility in gas prices. [EIAa]

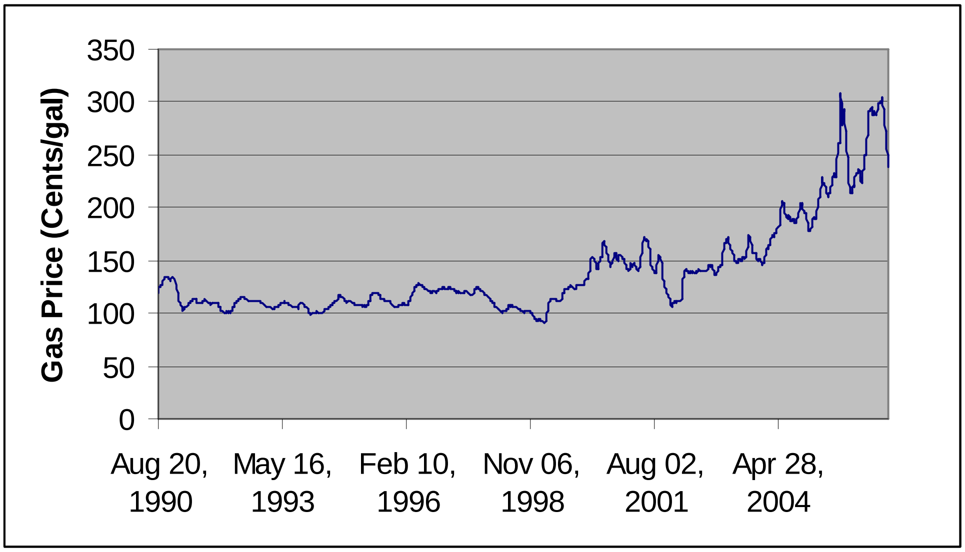

Figure 6: Historical Gas prices. [EIAa]

Gas prices recently reached a record high (in nominal terms), but have since dropped significantly. It is unlikely that the price of gasoline can trend upward indefinitely because sustained high gas prices will spur the development of alternative fuels such as ethanol, hydrogen, or unconventional sources of petroleum (tar sands, oil shale, coal-to-liquids, etc). At the same time, it is likely that there will continue to be significant upward pressure on gas prices deriving from a number of sources:

1.) Increasing demand, particularly from China & India
2.) Increasingly expensive recovery processes.
3.) Political instability and/or tenuous foreign relations with major oil producers.
4.) Potential for internalizing the environmental costs of gas – for example, through gas taxes.

It is important to build this instability into the system model; the volatility is the very reason we would like to build a more flexible HEV rollout strategy, while the long-term unpredictability will have a real impact on whether a mild- or full-hybrid should be pursued.

In light of this uncertainty, we might expect gas prices to follow a gradual upward trend over the project lifetime, but to exhibit significant volatility around this trend line. The EIA has projected that gas prices will increase at an annual real rate of 0.5% over the next 30 years [EIAc, Table 12]. Gas prices are assumed to trend upwards at this rate. Historically, going back to 1990, gas prices have exhibited average annual volatility of between 10 and 15% [EIAb]. Baseline evaluation will use these values for the basic trend and the price volatility.

3.3 Regulatory Environment

There are several options for incentivizing high efficiency vehicles. These include vehicle subsidies, command-and-control standards, or gasoline taxes. All three of these methods are currently in use. For example:

- Hybrid vehicles get a federal income tax break of up to $3400; in addition, several states also give tax credits or tax deductions, also on the order of $3000 [EPAb].
- The coporate average fuel economy (CAFÉ) standards require that each auto manufacturer meet minimum sales-weighted fuel economy levels.
- The federal government charges a gasoline tax on the order of $0.40/gallon.

It is not obvious how to model this uncertainty. It is likely that all of these regulatory structures will persist over the life of the project, but it is not clear to what extent. Changes in the gasoline tax are included in our assumptions about the evolution of fuel price. The other two factors are not variables for which one value is clearly more probable than another value; nor is it likely to vary from year-to-year in a “random” fashion (except insofar as a policy can get phased in or phased out).

To model this uncertainty, we will assume an incentive that is tied to the estimated lifetime fuel savings. This incentive will act to increase the profit on each vehicle sold. The baseline scenario will assume no rebate; however, subsequent analysis will assess the impact of a $0.25/gallon and $0.50/gallon rebate.

3.4 Battery Evolution

The costs of both NiMH and Lithium-ion batteries are likely to decrease from today's levels. Both will experience downward price pressure arising from increasing production volumes and improved manufacturing processes. At the same time, both chemistries might also experience upward price pressure due to the rising costs of commodity materials. These material costs are influenced by many of the same factors that influence price fluctuations in oil (discussed above), and are also influenced directly by the price of oil; as such, we might also expect high volatility.

For the above factors, the relative improvement for both batteries should be similar for both chemistries: both NiMH & Li-ion should be similarly advantaged (or disadvantaged) by economies-of-scale and by commodity material price fluctuations.

In addition to these influences, lithium-ion technology is likely to significantly improve beyond present-day levels. NiMH, on the hand, is a more mature technology that is nearing fundamental limits on its capability. Improvements to li-ion batteries are likely to take the form of: a.) Improved durability, which will lower the risk factor associated with battery warranty; and b.) Improved specific power and specific energy. Because improvements to specific energy imply that less active material is required for the same level of performance, these improvements can decrease battery price. Historically, li-ion batteries improved between 3% and 10% every year (in terms of specific energy (W-hr/kg)) from 1990-2001, at an average rate of about 5% every year [Battery Industry Development]. Since that time, this growth rate has slowed. However, recent advances in material properties and nano-engineering show some promise of continuing along these historic trajectories. The current state-of-the art for an advanced lithium-ion battery yields a specific energy of ~150 W-hr/kg [Saft]. It has been estimated that the best case scenario over the mid-term for a lithium-ion battery is 300 W-hr/kg [Chiang]. This represents an improvement of 3.5% per year for 20 years.

We can view this 3.5% growth rate as a maximum, and 0% growth as a minimum. We will assume that half of the potential gets realized, for a baseline cost reduction of 1.75% per year – a 20 year improvement of 41% over the present-day state-of-the-art. To assess the impact of the incremental but *varying* rates of change in these technical improvements, we can use a normally distributed probability curve centered at the mid-point of this best-case and worst-case scenario. This is a detail that will be accounted for later.

For initial analysis, the projected battery costs at the project midpoint will be used throughout the life of the project. This assumption will be varied to get a sense of how the differing rates of change will effect the project's value proposition.

3.5 Summary of Uncertainty Analysis

The previous section is meant to give a broad overview of the various types of uncertainties that can impact the system. Due to constraints in scope, the proceeding analysis will focus primarily on the impact of volatility in gas prices, though some consideration will also be given to changes in lithium-ion battery cost arising from evolving technology, improved economies of scale, and changes in commodity materials prices. These two factors (fuel cost and battery price) are considered the highest risk elements influencing our choice of optimum business strategy.

For the initial, single-variable analysis, we will assume that:

1.) No carbon tax is in effect, meaning that profit is directly proportional to vehicle sales.
2.) Vehicle prices are based on the projected battery costs at the project midpoint. This is 85% of the starting value shown in Table 3.

Later sections will incorporate the impact of these two factors (carbon tax and non-static rates of improvement), first by testing the sensitivity of results to different assumptions, and then by undertaking a Monte-Carlo analysis using different distributions.

4 Static Assumptions

This section will compare the two business strategies using a series of static assumptions. This is useful for illustrating the mechanics of the decision process and it provides a sense of market conditions under which the two different business strategies make sense. Subsequent analysis will examine the effect of incorporating uncertainty which more accurately reflects the range of possible outcomes.

Figure 7 shows the NPV of the different vehicle options as a function of fuel price using the projected li-ion battery prices at the project midpoint. As is apparent from the plot, different vehicle configurations give optimum results for different fuel price scenarios. Figure 8 shows the NPV of the flexible option when we use the optimum choice at each price point. This curve is obtained by simply tracing the most favorable (highest NPV) data point for each of the four vehicle options at the relevant fuel price.

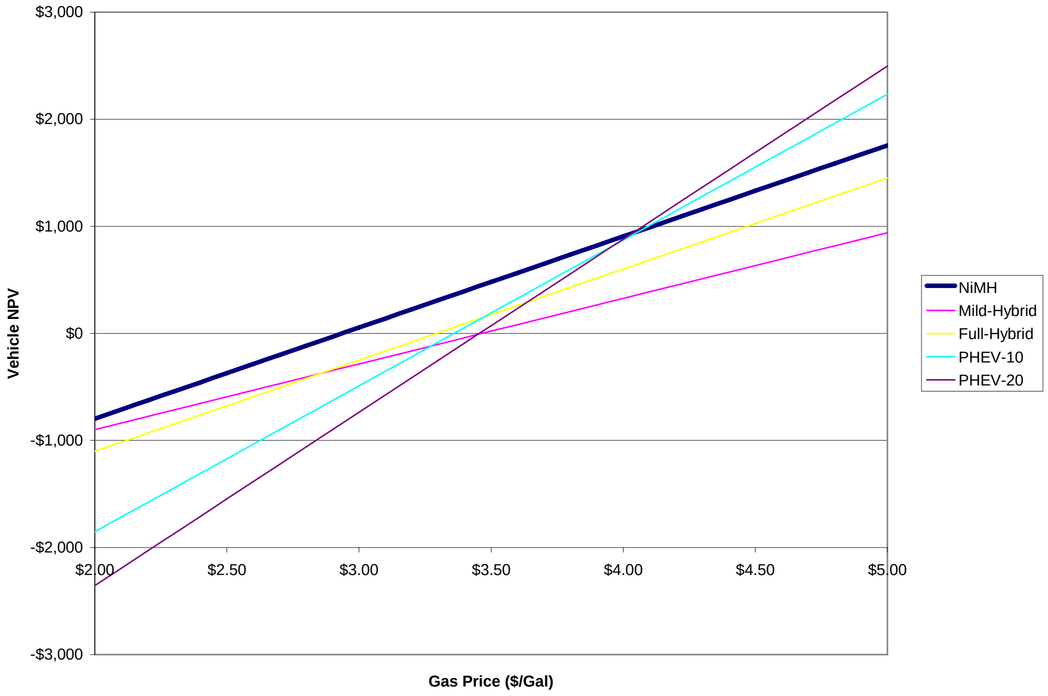

Figure 7: NPV of Different Vehicle options.

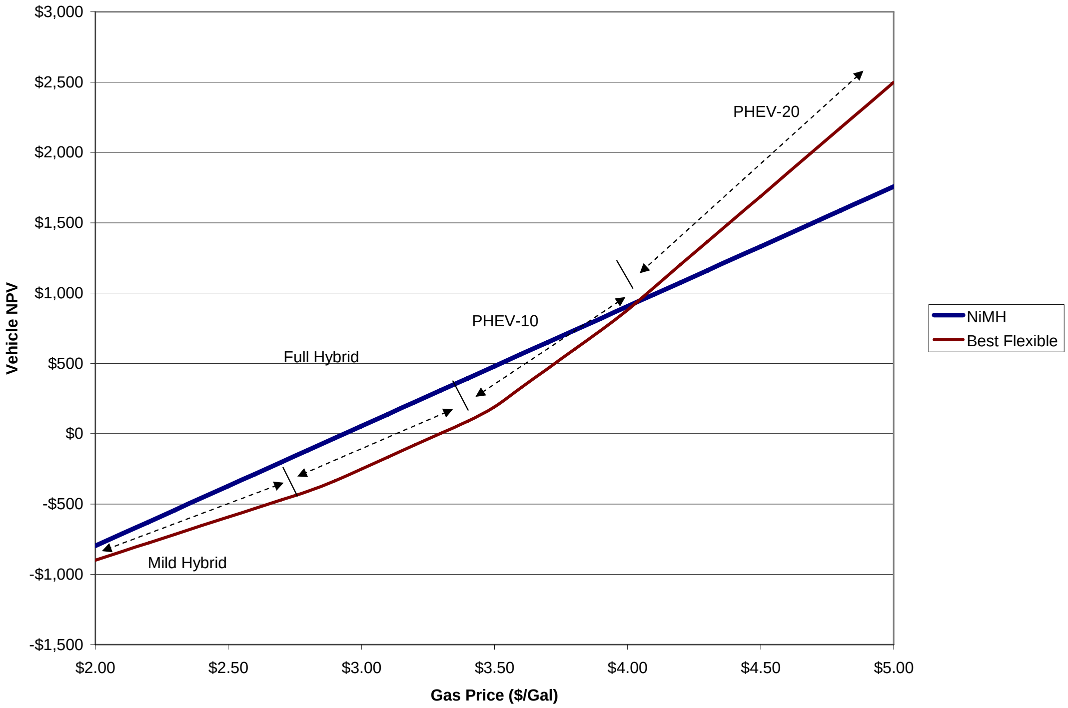

Figure 8: Price points for exercising different options in the flexible strategy.

Projecting this data into the previously described demand function gives the results shown in Figure 9. As is apparent, the breakeven fuel cost between the two strategies within this static analysis is about $4.00/gallon.

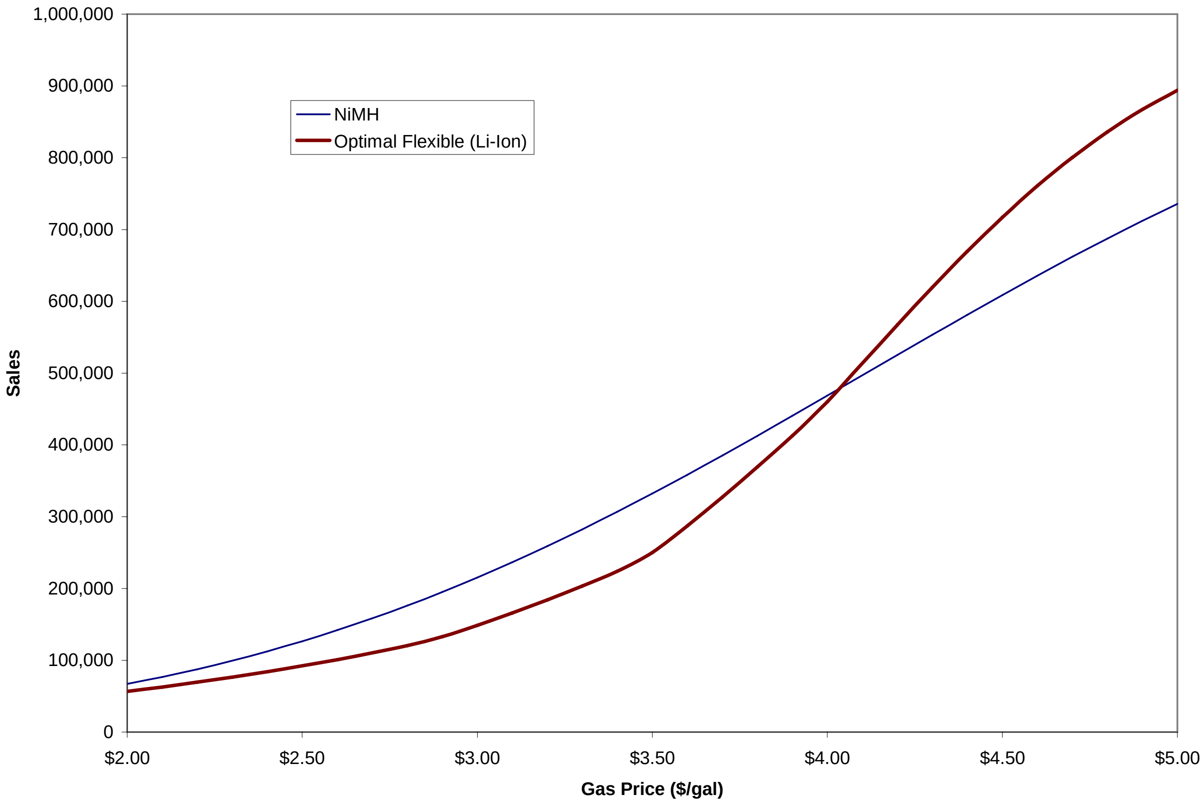

Figure 9: Comparative vehicle NPV (top) and subsequent market share (bottom) for the flexible and the inflexible case.

5 Decision Tree

A more nuanced approach to this evaluation uses a decision tree to model the evolution of expected sales volume over a period of 6 years; this will be implemented as a 2-stage decision tree with each time step representing 3 years. This decision tree will focus on the impact of the volatility in gas prices while holding technology improvement constant.

For this analysis, gas prices are varied by 0%, +15%, or -10% from their relevant future value for each of two time steps in the decision tree. (This means that at each time step, the gas price may vary by 0%,-10%, or 15% from its current value). It was assumed that each of the three outcomes was equally likely at both time steps. The initial gas price is assumed to be \$3.00/gallon. For the first time step, the flexible option implements the full-hybrid (as it is the optimum choice at gas = \$3.00/gallon). For the second time step, depending on whether fuel prices rose, declined, or stayed the same, a different vehicle option is chosen. These assumptions are summarized in Table 4.

State	**Change**	**Probability**
High	+15%	33.3%
Medium	0%	33.3%
Low	-10%	33.3%

Table 4: Decision Tree Input Parameters

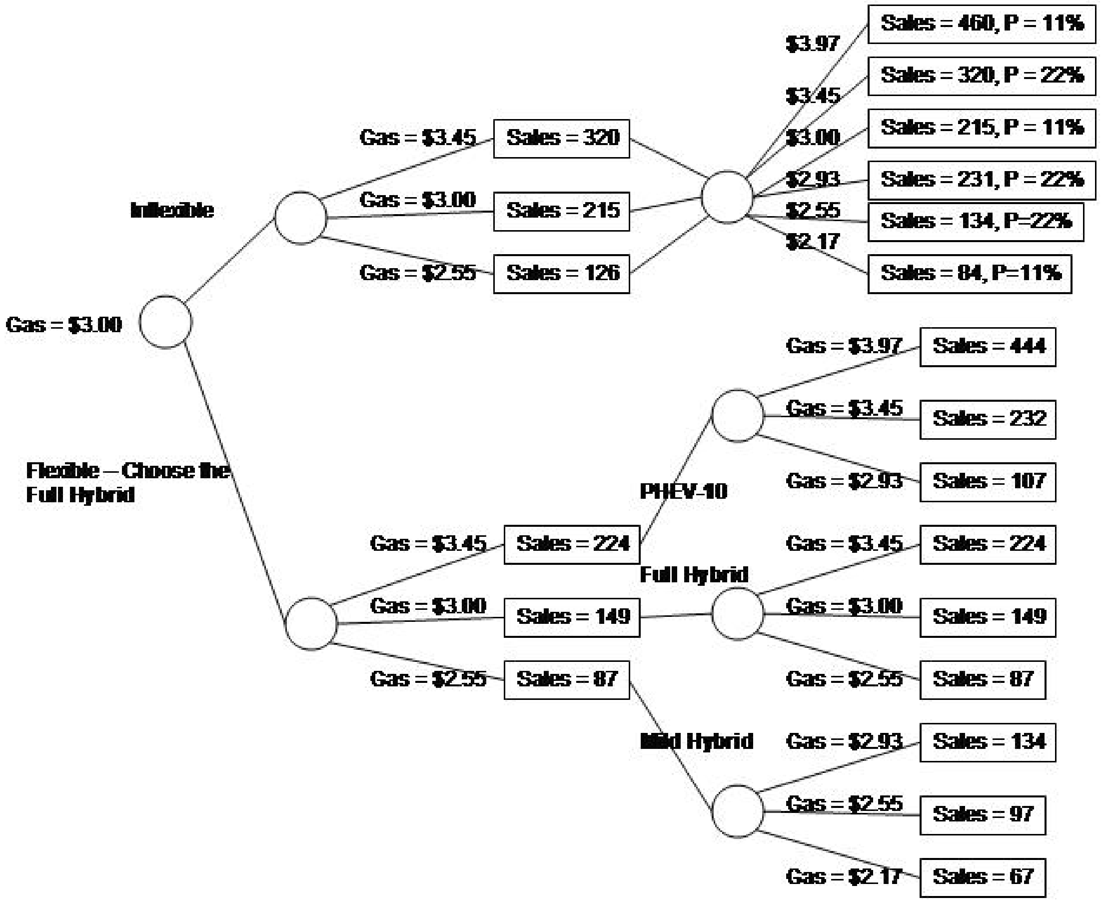

Figure 10: 2-Stage Decision Tree for different gas price scenarios. Sales figure in thousands.

Figure 10 shows the detailed decision tree used for analysis of this problem. Note that for the flexible platform, the actual strategy pursued is noted in bold at each node of the decision tree. Each node also shows the current price of gas. Solving the decision tree for the expected values at the end of the two time steps gives the following results:

	Yr 1	**Yr 2**
Expected Sales, NiMH (inflexible)	220K	234K
Expected Sales, Li Ion (flexible)	153K	171K

Table 5: Decision Tree Analysis Results

Over this two-period analysis, the NiMH strategy is clearly superior. As discussed in the previous section, the NiMH strategy is more profitable than the li-ion batteries at fuel prices below $4.00/gallon. Over this two-stage analysis, gas prices do not get high enough for the flexible option to be worth it. At sustained higher prices, it is possible that the flexible plan becomes the more profitable option.

6 Lattice Analysis

Using inputs similar to those used in the decision tree, the lattice allows us to trace the evolution of gas prices for the entire duration of the project. This is a powerful method to evaluate whether the additional costs of the flexible approach are justified.

For this analysis, we again focus on variations in fuel cost. Using the predicted price evolution (detailed in Section 6.1), the lattice analysis will be applied to the vehicle models under several different assumptions about rates of technological change (and associated price decrease).

6.1 Lattice Calibration

This section will characterize the price evolution, the probability distribution, and the expected value of gas prices by applying estimates of future appreciation rate and volatility. This analysis will again use the projected midpoint vehicle prices while varying gas price throughout the life of the project. The following parameters are used to calibrate the lattice:

Initial Value of gas:	**$2.75**	per gallon
Volatility (per year):	**10%**	
Rate of Appreciation (per year):	**0.5%**	
Length of 1 period:	**3 yrs**	

Table 6: Lattice Calibration parameters

Applying these values, we can define the up value (u), down value (d), and the probability of the up value (p) as follows:

u = 1.19
d = .84
p = .54

This gives the following price evolution for the price of gasoline and the probability distribution of these prices over a period of 18 years (six 3-year periods):

Period						
0	1	2	3	4	5	6
$2.75	$3.27	$3.89	$4.62	$5.50	$6.54	$7.77
	$2.31	$2.75	$3.27	$3.89	$4.62	$5.50
		$1.94	$2.31	$2.75	$3.27	$3.89
			$1.64	$1.94	$2.31	$2.75
				$1.38	$1.64	$1.94
					$1.16	$1.38
						$0.97

Table 7: Price evolution of gasoline over 6 periods.

Period						
0	1	2	3	4	5	6
1.00	0.54	0.30	0.16	0.09	0.05	0.03
	0.46	0.50	0.40	0.29	0.20	0.13
		0.21	0.34	0.37	0.33	0.27
			0.10	0.21	0.28	0.31
				0.04	0.12	0.19
					0.02	0.06
						0.01

Table 8: Probability distribution of price evolution

Combining these results gives the following probability distribution and expected value for gas prices at each period:

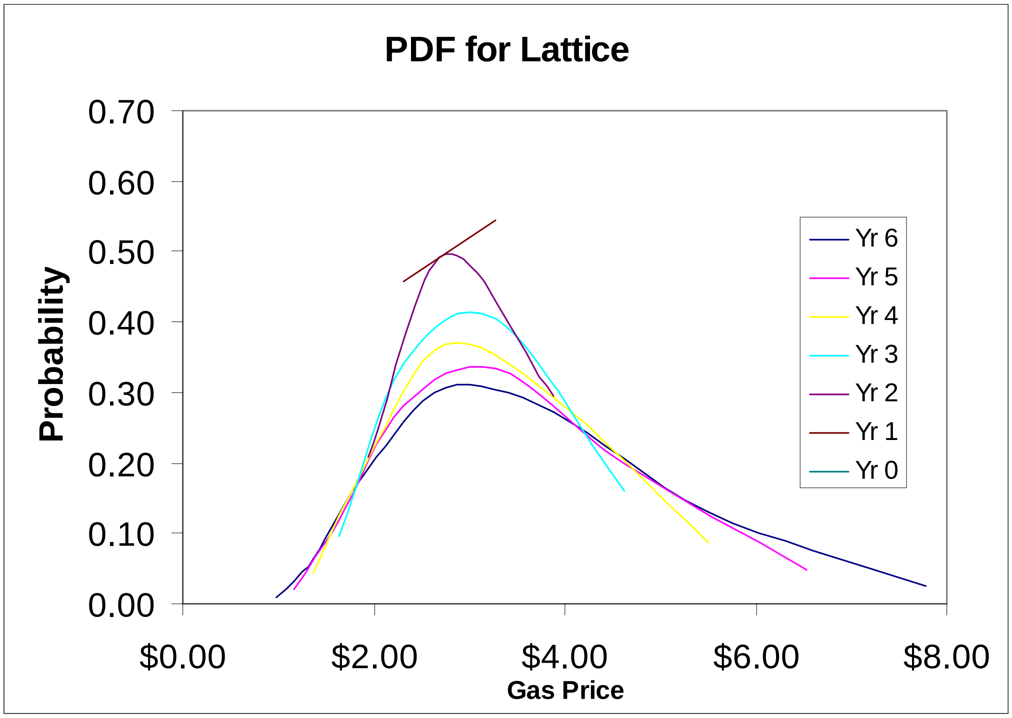

Figure 11: Probability distribution of price evolution

Expected values:	$2.75	$2.83	$2.92	$3.01	$3.10	$3.19	$3.29

Table 9: Table of expected values of gas prices

6.2 Lattice Results

Using the lattice structure defined in the previous section, we are now in position to evaluate the lattice evolution over time for the both the flexible and inflexible scenarios. For the flexible case, each build decision for the next period is dictated by maximizing the expected sales volume in the future state. The inflexible strategy has only a single vehicle configuration, so no build decision is necessary.

For reference, the following table shows the range of fuel price points over which each of the flexible options represents the optimal decision:

Mild	<\$2.86
Full	\$2.86-\$3.46
PHEV-10	\$3.46-\$3.96
PHEV-20	>\$3.96

Table 10: Range of fuel price at which each option is optimal

For example, from the high state in the 2nd to last period, gas can either be \$5.50 or \$7.77/gal in the final period (see Table 7); the expected for value for gas (~\$6.70/gal) dictates that we build the PHEV-20. Applying this methodology to every state leads to the following build decisions for the flexible strategy:

Period					
1	2	3	4	5	6
Full Hybrid	PHEV-10	PHEV-20	PHEV-20	PHEV-20	PHEV-20
	Mild Hybrid	Full Hybrid	PHEV-10	PHEV-20	PHEV-20
		Mild Hybrid	Mild Hybrid	Full Hybrid	PHEV-10
			Mild Hybrid	Mild Hybrid	Mild Hybrid
				Mild Hybrid	Mild Hybrid
					Mild Hybrid

Table 11: Build strategy for the flexible option

To actually determine the sales volume (and hence profitability), we follow the following procedure:

1.) Compute the sales/profit at each possible lattice outcome for each possible build decision.
2.) For the flexible strategy, select the option that maximizes profit during the next period.
3.) Working backwards through the lattice (and using the appropriate choice at each point throughout the flexible lattice), at each decision point, compute the cumulative expected sales by calculating:

$$\text{Cumulative Sales} = \text{Sales}_{\text{Current Pd}} + (P_{\text{Hi}})(\text{Cum Sales}_{\text{Next pd, Hi}}) + (1-P_{\text{Hi}})(\text{Cum Sales}_{\text{Next Pd, Low}})$$

Where:

P_{Hi} is the probability of going to the high state

$\text{Sales}_{\text{Current Pd}}$ is the sales volume at current gas prices

$\text{Cum Sales}_{\text{Next Pd, Hi}}$ is the cumulative future sales from the high state during the next period

$\text{Cum Sales}_{\text{Next Pd, Low}}$ is the cumulative future sales from the low state during the next period

Following the above procedure and working backwards through the lattice, we can project the expected total sales volume (through the life of the project) from each state as shown in Table 12 and Table 13. In these tables, each cell may be interpreted as the expected sales for the life of the project from the given state. (Hence, the numbers in the period 5 cells represent “expected cumulative sales from period 5 & period 6”). **For more details on the lattice procedure used, see the appendix in Section 12.**

Period					
1	2	3	4	5	6
1,192,471	1,541,149	1,894,775	2,016,780	1,725,202	986,389
	573,826	702,996	847,397	922,788	689,311
		271,583	292,198	292,340	237,103
			133,390	121,237	84,668
				62,584	41,226
					23,128

Table 12: Expected sales volume throughout the project, flexible.

Period					
1	2	3	4	5	6
1,402,474	1,693,829	1,899,353	1,898,549	1,580,370	917,081
	724,865	872,712	971,614	932,934	639,093
		342,238	390,917	398,969	303,351
			150,432	150,529	115,093
				60,944	44,308
					19,621

Table 13: Expected sales volume, inflexible.

When we compare the two different strategies, we find that, in terms of value proposition to the consumer (strictly in terms of NPV), the NiMH option shows better performance under low- and mid-level scenarios, while the flexible strategy does better during high fuel price scenarios. This behavior is illustrated in Figure 12, which compares the evolution of vehicle NPV of the two different strategies throughout the project lifetime.

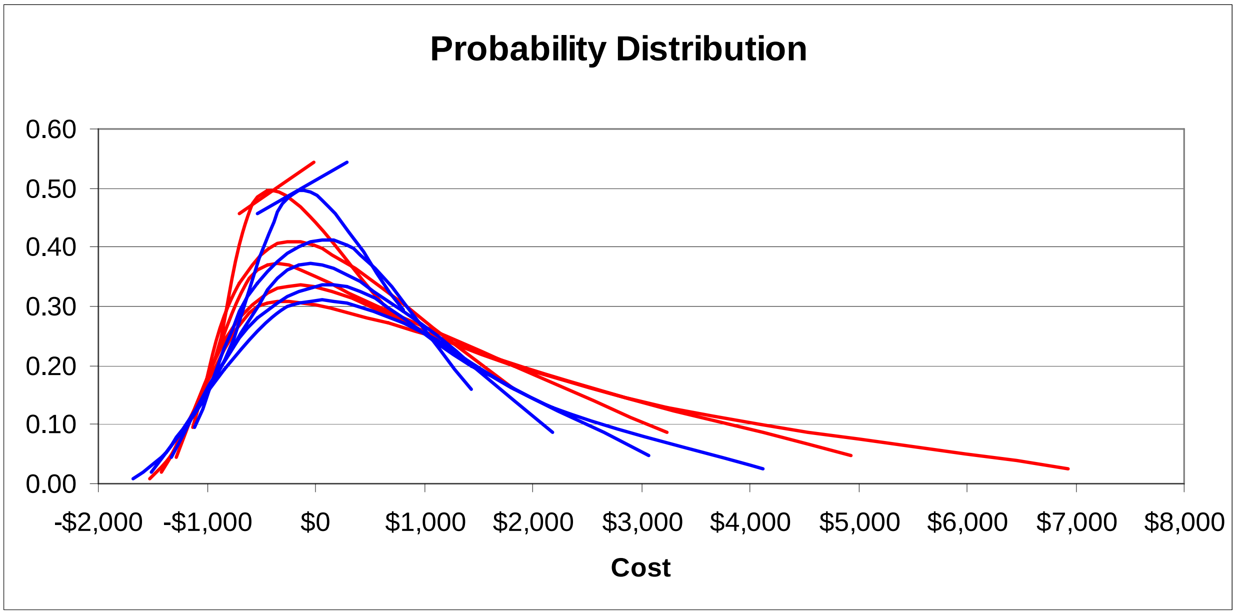

Figure 12: Evolution of NPV under different business strategies. The red represents the flexible strategy. The blue shows the inflexible (NiMH) option.

However, when we translate NPV into sales volume (Figure 13), the flexible strategy looks much worse than the inflexible approach. Here we see that the 10% value-at-risk (VAR) is nearly indistinguishable for the two strategies, while the sales volume under mid-range scenarios dramatically favors the NiMH approach. Under the high-end scenarios, both projects again show very similar performance.

The narrow difference for the high-end results is a result of the fact that vehicle sales tend to saturate at a level of profitability that is obtainable with even the limited benefit of the NIMH approach. For example, at NPV>$2500, sales volume exceeds 90% of the maximum sales. In this respect, the flexible option’s high-end value proposition delivers only marginal benefit.

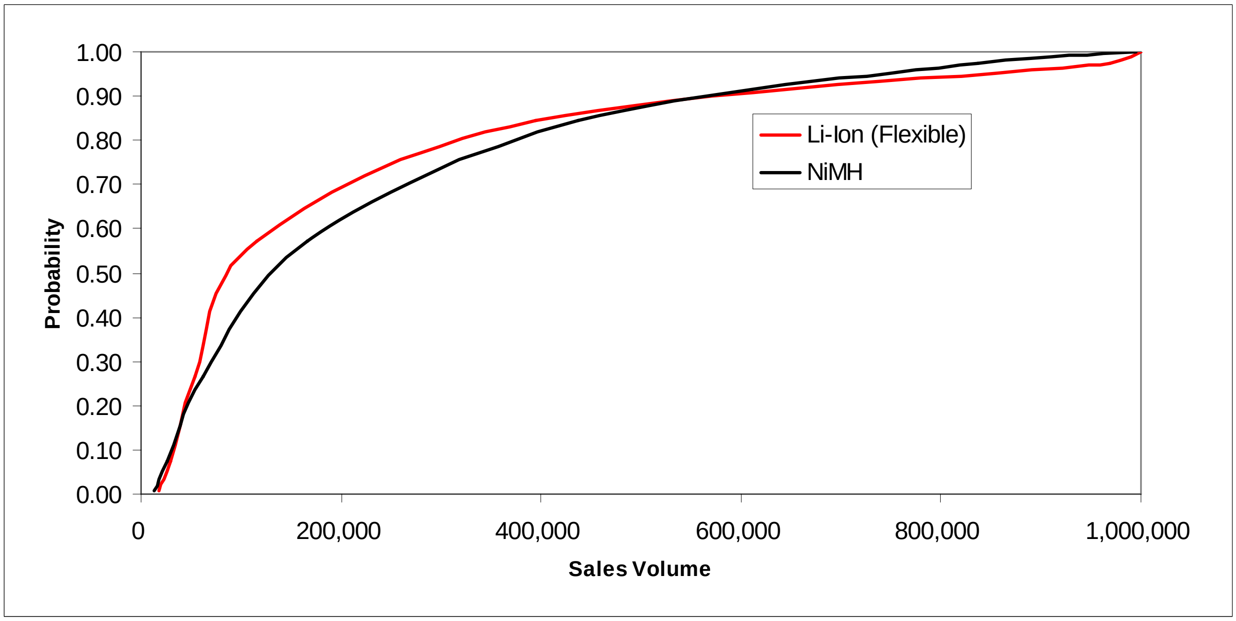

Figure 13: Cumulative probability distribution of yearly sales using different build strategies for period 6.

Assuming no carbon tax, the inflexible strategy is the better approach. For example, when we compare the expected sales of the two different strategies in each period, the inflexible approach comes out ahead:

Period	Li-Ion	NiMH
1	136,034	195,727
2	170,957	224,961
3	218,270	252,413
4	243,660	276,802
5	278,577	298,580
6	296,803	318,261
Total	**1,344,300**	**1,566,745**

Table 14: Expected yearly sales during each period for the different strategies

7 Sensitivity to Carbon Tax

The previous section assumes that different vehicles confer no additional benefit beyond that associated with higher sales. However, there is some chance that government incentives might subsidize car manufacturers to encourage more fuel efficient vehicles. One way to do this is via a rebate that scales with lifetime fuel savings. This section will examine the impact of several different levels of rebate. Under these conditions, the profit for a vehicle platform during any given year is given by:

Profit = (sales) [(baseline profit) + (yearly fuel savings) (15 years)(rebate per gal)]

Baseline profit ($2000/vehicle) and yearly fuel savings (varies depending on platform) are both as specified in Table 2 and Table 3, respectively. We will examine the impact of a rebate of $0.25/gallon and a rebate of $0.50/gallon. This changes the profit for different vehicle configurations from a flat $2000 to the values shown in Table 15.

Vehicle Configuration	**$0.50/gal rebate**	**$0.25/gal rebate**
Full Hybrid, NiMH	$2938	$2469
Mild Hybrid, LI	$2675	$2338
Full Hybrid, LI	$2938	$2469
PHEV-10, LI	$3500	$2750
PHEV-20, LI	$3785	$2893

Table 15: Per-vehicle profit under different carbon tax scenarios

Using these criteria for weighing the different plans, we can apply a similar procedure to that described in 6.2 to characterize the lattice evolution of these scenarios. Unsurprisingly, the flexible strategy becomes more attractive than for the zero-rebate case. As before, the inflexible plan does a little bit better under moderate price scenarios; however, with a carbon tax, the flexible option has the potential for a big payoff in high fuel price scenarios.

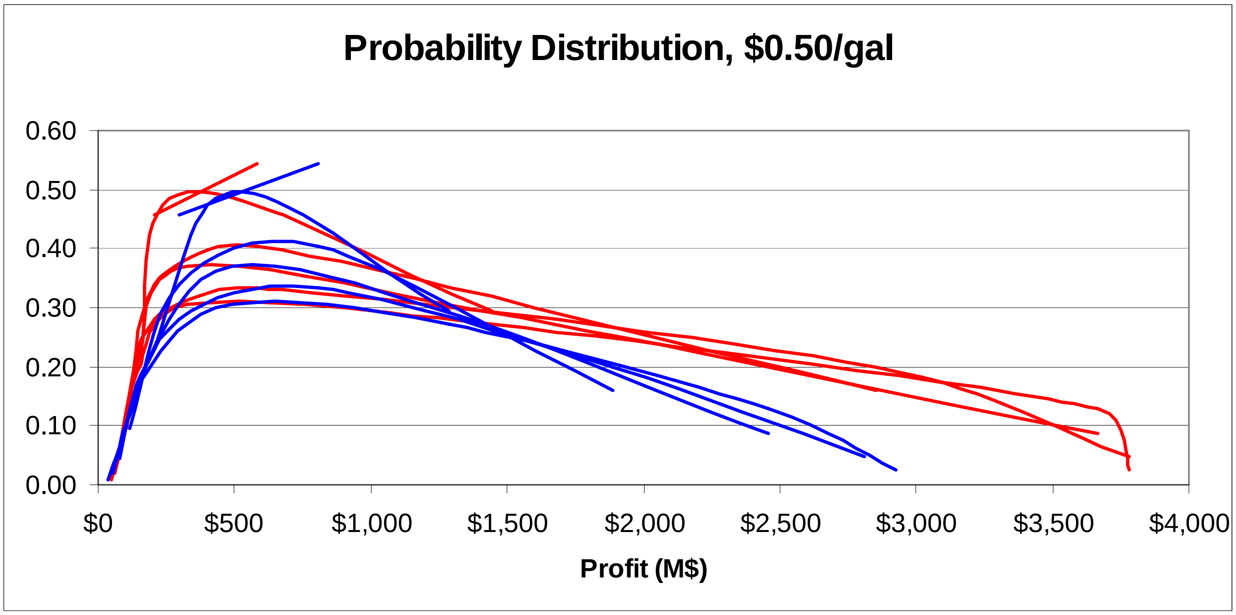

Figure 14: Evolution of probability distribution of profit over all periods. NiMH in blue, Li-ion in red.

Interestingly, while the incentive narrows the difference between the flexible and inflexible scenarios, it takes a fairly sizeable incentive to give a higher expected value for the flexible case. Figure 15 and Figure 16 show the cumulative probability of increasing profits under the two different carbon tax scenarios. In both cases, the inflexible plan has >80% chance of delivering higher profit, although the $0.50 case (Figure 15) has a high upside. The results of these scenarios show that the $0.50 rebate favors the flexible scenario, while the $0.25 rebate favors the inflexible case (see Table 16 and Table 17). The break-even point appears to be approximately $0.40/gallon.

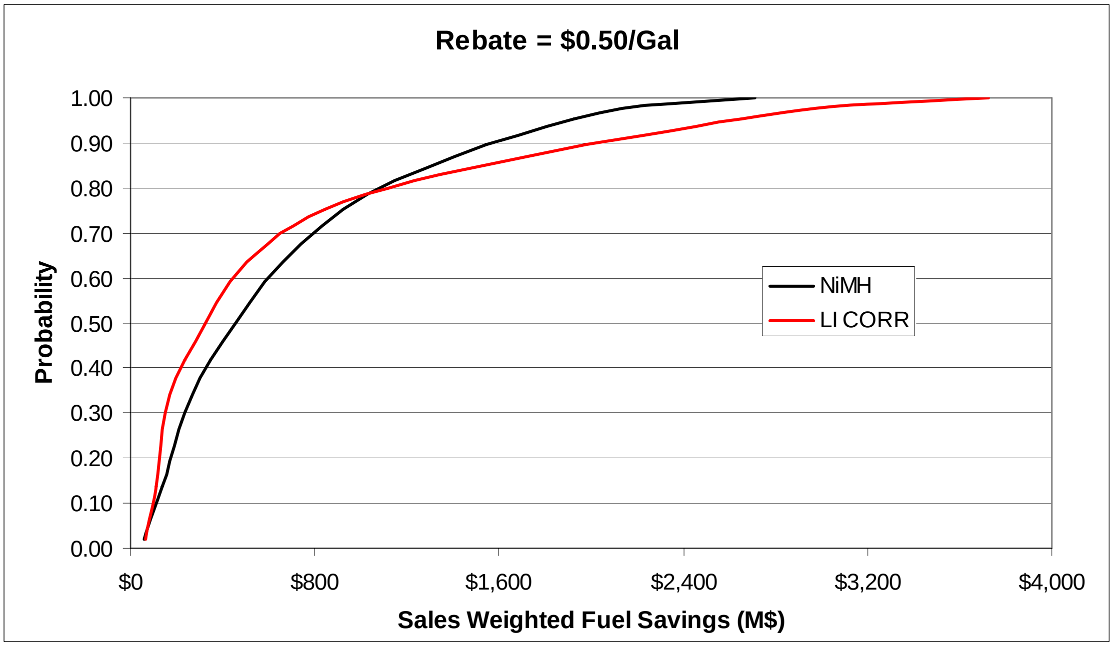

Figure 15: Cumulative probability of profit, Pd 6 @ $0.50/gallon

Period	1	2	3	4	5	6	Total
Inflexible	$575	$661	$741	$813	$877	$935	$4,602
Flexible	$400	$566	$755	$857	$996	$1,066	$4,639

Table 16: Profit, in M$, for $0.50/gallon rebate

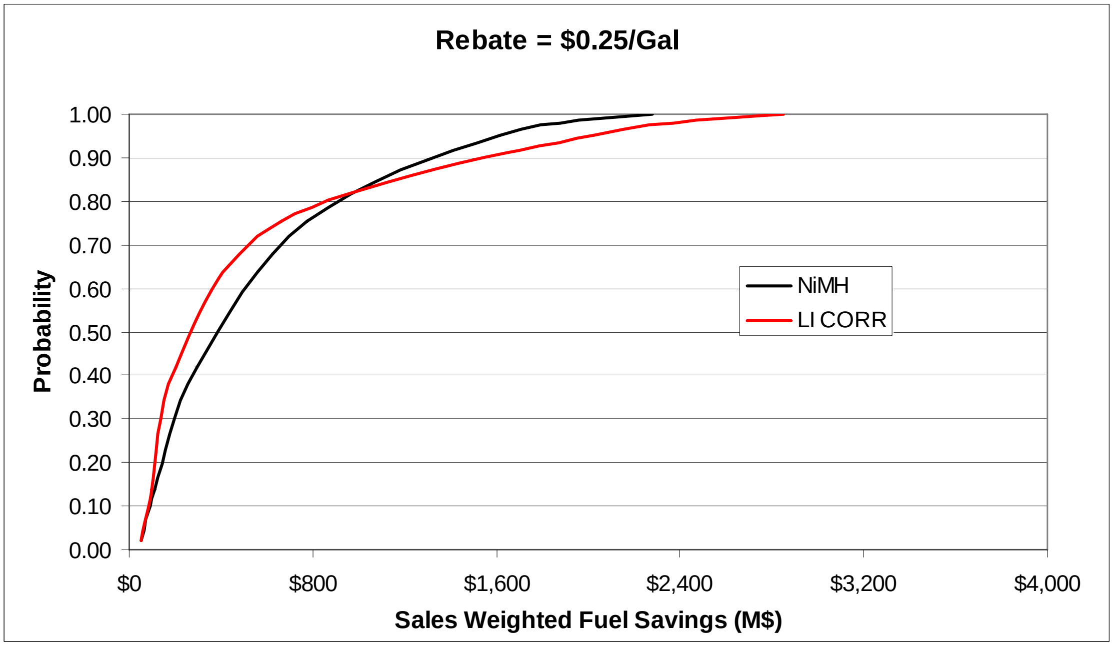

Figure 16: Cumulative probability of profit, Pd 6 @ $0.25/gallon

Period	1	2	3	4	5	6	Total
Inflexible	$483	$555	$623	$683	$737	$786	$3,868
Flexible	$336	$454	$596	$672	$776	$830	$3,664

Table 17: Profit, in M$, for $0.25/gallon rebate

8 Sensitivity to Technological Improvement

The other important uncertainty that warrants attention is the sensitivity to different rates of technological improvement. Thus far, we have used a midpoint estimate for the price decreases associated with improving lithium-ion battery technology of 1.75%. This section of the paper will address the issue by testing how different rates of change might change the outcome of our evaluation. For this analysis, it is assumed that there is no carbon tax in effect.

Figure 17 shows the total sales volume over the project lifetime under different (static) fuel price scenarios for different rates in price decrease for lithium ion batteries. The 3% rate of improvement – in this analysis considered optimistic – appears to be optimal over any fuel price scenario. Note that the difference is minimal at gas prices <$3.00/gallon, at which point it diverges – this is the point at which we start producing plug-in hybrid vehicles, and the flexibility becomes a distinct advantage. The 1.75% rate of improvement becomes more profitable than the inflexible result at ~$4.00/gallon. This is essentially the same answer that we got using the project midpoint value for vehicle cost (see Figure 8, for example), which in some sense validates earlier results.

Additional study has shown that, at rates of change >2.5%, the expected value of the flexible strategy surpasses that of the inflexible plan.

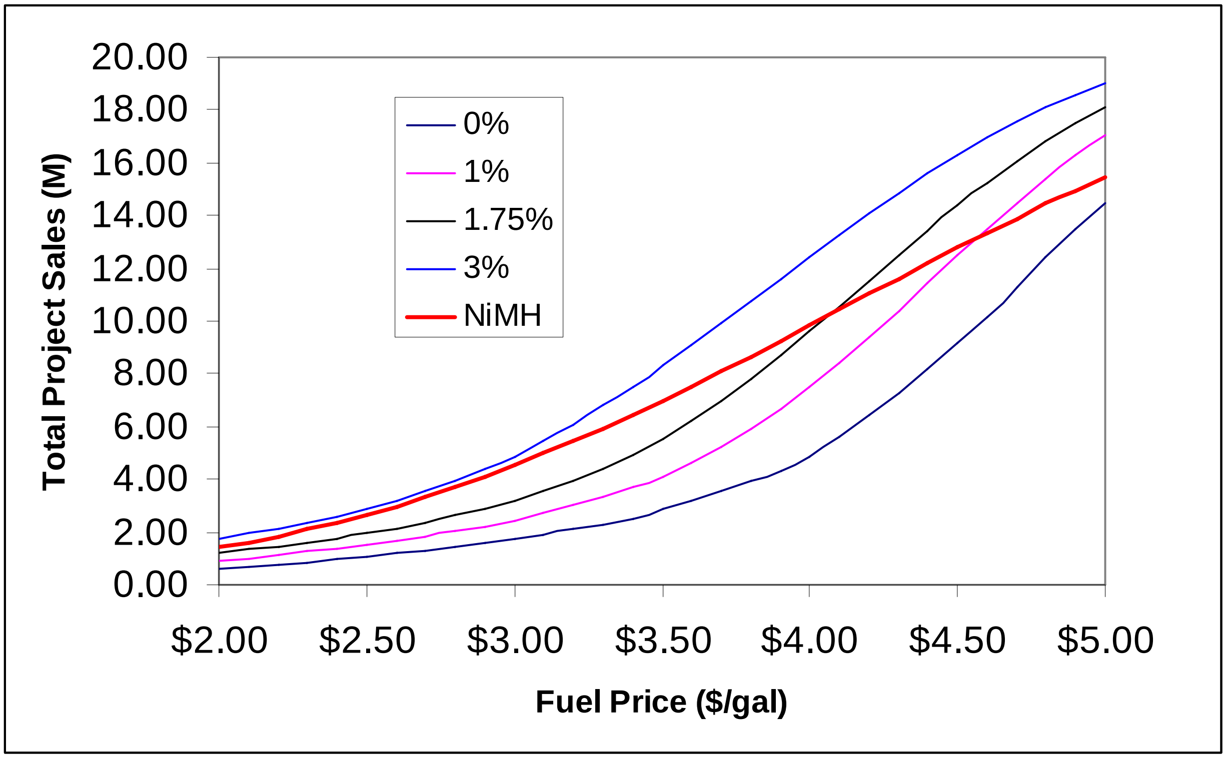

Figure 17: Impact of differing rates of technological improvement of lithium-ion batteries on vehicle sales.

9 Monte Carlo Analysis

As a final piece of the analysis, this section will integrate the fuel and technical risk into a single model using Monte Carlo simulation. The lattice analysis assumes an average value for vehicle purchase price and holds this constant throughout the project. The Monte Carlo simulation allows us to test the impact of varying rates of change of technical development. For this simulation, 1250 simulations were run for each of six 3-year time periods using a normally distributed rate of change in gas price (same assumption as in the lattice model), and a normally distributed decrease in purchase price (mean = 1.75%, standard deviation = .35%).

Interestingly, when we include the declining purchase price over the life of the project, the flexible project becomes worse. For example, using these assumptions, even the $0.50/gallon rebate continues to favor the inflexible option: for this case, $EV_{flexible}$ = $3.72B vs $EV_{inflexible}$ = $3.9B. Figure 18 shows the cumulative probability for the $0.50/gallon case; though it looks qualitatively similar to previous results, the difference in upside profits between the flexible and inflexible options have narrowed.

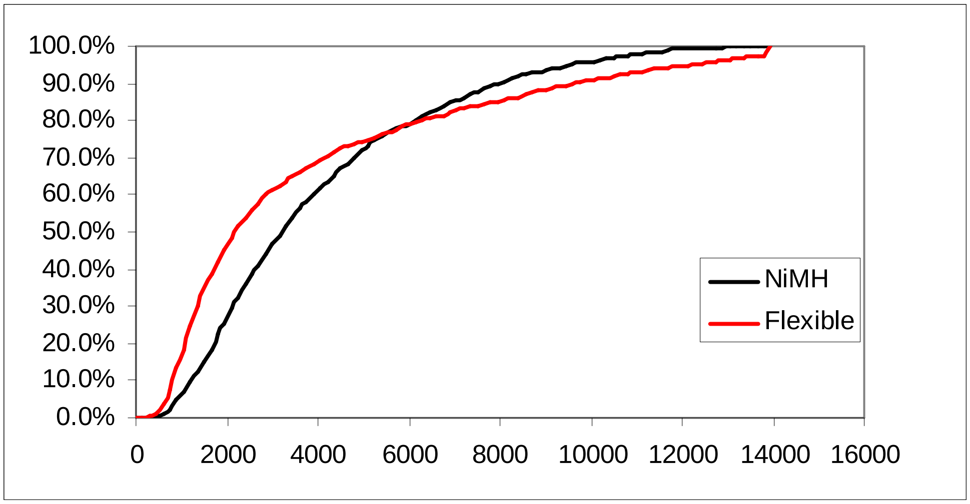

Figure 18: Cum. Probability, in M$, for $0.50/gallon Monte Carlo analysis.

10 Conclusion & Reflection

It appears that transitioning to lithium-ion batteries is premature for this project. This is because the higher capital expense of the battery compared to the NiMH baseline makes the car less profitable over most mid-range scenarios. At the low end, the flexibility to implement a mild-hybrid option is advantageous, but not significantly so. At the high-end, the plug-in capability offered by the flexible plan is quite attractive as a value proposition to the consumer; however, the demand model chosen for this analysis shows the market saturating even without this added value.

This conclusion is robust across a range of conditions and analysis techniques. Both the lattice analysis and decision tree deliver qualitatively similar answers, though the lattice method is regarded as a more appropriate approach for this evaluation. Because the task of evaluating the decision tree grows exponentially as we add options and extend growth period, it is impractical to use it to undertake a complete analysis for the duration of the project while maintaining a nuanced assessment of variation within the project. The lattice approach allows us to undertake a robust model of the key uncertainty (fuel price); iterating several times allows us to test it under several different regulatory and technical solutions.

Either higher than expected rates of technical change or a significant fuel economy incentive (in this case, modeled as a carbon rebate) could shift the balance towards the flexible scenario. In particular:

1.) If lithium-ion technology improves faster than expected (>2.5%/yr), the flexible option becomes more attractive.
2.) Rebates >$0.40/gallon fuel savings make the flexible option more attractive, although Monte Carlo analysis suggests that the price reduction over time further moderates the attractiveness of the flexible option.

In addition, though not explicitly evaluated, higher volatility or growth rate in fuel price, as well as shifts in consumer behavior would have a significant impact. In this vein, it should be emphasized that the consumer demand function assumed is not well grounded.

In some ways, I feel I shoe-horned the project to fit within the context of the class, but the process has been useful in illustrating the type of project for which decision analysis is most useful. I found the option identification portion of this project to be the most challenging component. I wanted to do something in the field of advanced automotive powertrains; I had initially framed the project as a trade-off between a start-stop (very mild) hybrid and a platform similar to the flexible platform evaluated in the final analysis. However, I found that the flexible platform was technically superior to the start-stop platform with or without the flexibility (i.e., selecting only the full hybrid was better). To make the project more interesting, I adjusted the project to evaluate which battery chemistry to use for next-generation vehicles, which is still an open question.

This project has helped me apply decision analysis to a field that is related to my line of research.

In particular, I found that the lattice analysis is a good approach for modeling a single key uncertainty; as discussed above, the decision tree quickly becomes unwieldy. I also found the Monte Carlo method very useful for integrating several different uncertainties into a single model, although it may not have been necessary for this project. It was quite unwieldy compared to the lattice method, as it involved >1000 trials for each of 6 time periods. I am glad to have implemented the Monte Carlo analysis, as this seems to be a particularly robust decision analysis tool.

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12 Appendix: Lattice Calculations & Spreadsheet

The following tables show the yearly sales under different build scenarios for the flexible strategy:

Yearly Sales, Mild Hybrid

1	2	3	4	5	6
175,210	268,325	404,288	580,978	768,990	914,202
77,393	115,181	175,210	268,325	404,288	580,978
	53,622	77,393	115,181	175,210	268,325
		38,472	53,622	77,393	115,181
			28,614	38,472	53,622
				22,041	28,614
					17,547

Yearly Sales, Full Hybrid

1	2	3	4	5	6
197,428	340,128	543,632	767,289	928,897	990,481
62,998	111,270	197,428	340,128	543,632	767,289
	36,645	62,998	111,270	197,428	340,128
		22,191	36,645	62,998	111,270
			14,082	22,191	36,645
				9,382	14,082
					6,556

Yearly Sales, PHEV-10

1	2	3	4	5	6
166,146	394,528	714,706	940,592	996,928	999,983
19,877	59,399	166,146	394,528	714,706	940,592
	6,684	19,877	59,399	166,146	394,528
		2,365	6,684	19,877	59,399
			904	2,365	6,684
				378	904
					174

Yearly Sales, PHEV-20

1	2	3	4	5	6
128,169	381,518	754,820	969,148	999,462	1,000,000
7,641	33,171	128,169	381,518	754,820	969,148
	1,742	7,641	33,171	128,169	381,518
		421	1,742	7,641	33,171
			113	421	1,742
				34	113
					12

Using this build data, we can determine the expected sales for the next period for each build choice by using:

$$\text{Expected Sales} = (P_{Hi})(\text{Sales}_{Hi}) + (1-P_{Hi})(\text{Sales}_{Low})$$

Expected Sales, Next Period: Mild Hybrid

1	2	3	4	5	6
130,537	198,384	299,668	438,190	602,431	762,019
	87,067	130,537	198,384	299,668	438,190
		59,618	87,067	130,537	198,384
			42,201	59,618	87,067
				30,968	42,201
					23,560

Expected Sales, Next Period: Full Hybrid

1	2	3	4	5	6
136,034	235,609	385,521	572,206	752,947	888,550
	77,189	136,034	235,609	385,521	572,206
		44,361	77,189	136,034	235,609
			26,340	44,361	77,189
				16,341	26,340
					10,645

Expected Sales, Next Period: PHEV-10

1	2	3	4	5	6
99,345	241,475	464,179	691,205	868,038	972,859
	35,324	99,345	241,475	464,179	691,205
		11,879	35,324	99,345	241,475
			4,044	11,879	35,324
				1,457	4,044
					570

Expected Sales, Next Period: PHEV-20

1	2	3	4	5	6
73,124	222,428	468,629	700,778	887,734	985,910
	18,817	73,124	222,428	468,629	700,778
		4,344	18,817	73,124	222,428
			998	4,344	18,817
				244	998
					66

To determine the appropriate strategy for each period, we need simply select the option that maximizes sales for each period. The specific build decisions are shown in Table 11, reprinted below for clarity:

Build Decisions

1	2	3	4	5	6
Full Hybrid	PHEV-10	PHEV-20	PHEV-20	PHEV-20	PHEV-20
	Mild Hybrid	Full Hybrid	PHEV-10	PHEV-20	PHEV-20
		Mild Hybrid	Mild Hybrid	Full Hybrid	PHEV-10
			Mild Hybrid	Mild Hybrid	Mild Hybrid
				Mild Hybrid	Mild Hybrid
					Mild Hybrid

Expected Sales, Next Period: Optimum Flexible

1	2	3	4	5	6
136,034	241,475	468,629	700,778	887,734	985,910
	87,067	136,034	241,475	468,629	700,778
		59,618	87,067	136,034	241,475
			42,201	59,618	87,067
				30,968	42,201
					23,560

In the above chart:
GREEN = Mild Hybrid
RED = Full Hybrid
PURPLE = PHEV-10
BLUE = PHEV-20

Finally, to compute the expected sales for the life of the project at each point in the lattice, we iteratively (starting with period 6) add the expected sales during the current period to the expected cumulative sales for the next period for the high and the low case.

Cumulative Expected Sales, Duration of the Project

1	2	3	4	5	6
				887,734 + (P_{Hi})(985,910) + (1-P_{Hi})(700,778)	985,910
				468,629 + (P_{Hi})(700,778) + (1-P_{Hi})(241,475)	700,778
				136,034 + (P_{Hi})(241,475) + (1-P_{Hi})(87,067)	241,475
				59,618 + (P_{Hi})(87,067) + (1-P_{Hi})(42,201)	87,067
				30,968 + (P_{Hi})(42,201) + (1-P_{Hi})(23,560)	42,201
					23,560

…

This gives the results shown in Table 12.