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| T3 ________________ | Problem Chosen | F3 ________________ |
| T4 ________________ | **C** | F4 ________________ |

**2011 Mathematical Contest in Modeling (MCM) Summary Sheet**
(Attach a copy of this page to each copy of your solution paper.)

Type a summary of your results on this page. Do not include
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# Executive Summary

The electric car market needs to be stimulated by investments in technology, infrastructure, and buying incentives. Modeling results have shown that without these influences, low market penetration rates will persist for decades. When coupled with investments in renewable electrical generation capacity, widespread use of battery electric vehicles has the potential to reduce yearly carbon emissions from the transportation sector by 53%. Annual oil consumption can likewise be reduced by 70% in 20 years. Furthermore, these investments would have the effect of creating several million jobs, reducing tailpipe emissions and decreasing human health costs.

Efforts to introduce electric vehicle fleets into urban environments are on the cusp of breaking through. Such a large scale shift in transportation technology could have wide-ranging effects that should be examined. This report analyzes the potential economic, environmental, social and health benefits and possible consequences of this market change. Though data for electric vehicle operation is limited, a simulation model was developed to predict the competition and interaction of two types of electric vehicles on the road. Model results were then used to quantify the consequences of the predicted market shifts.

A Lotka-Volterra ecological competition model was adapted to describe the behavior of the passenger vehicle market. The separate populations of gasoline-powered internal combustion engine vehicles (ICE), plug-in hybrid vehicles (PHEV) and battery-electric vehicles (BEVs) are assumed to perform in a similar manner to organisms competing for a shared, but limited resource. For organisms, this resource might be a food supply; in the vehicle market, manufacturers compete for consumer dollars. The Lotka-Volterra equations used describe the time rate of change for three dependent variables. These variables represent the population of registered vehicles of each type in an auto market. The model parameters describe growth rates, interspecies competition and a population carrying capacity. These parameters indirectly relate to consumer preferences, economic conditions, government influences and improvements in automotive technologies. Variables used in the model are listed in Table 0.1.

Intrinsic growth rates were assumed to be constant, but refinements to the

model could describe them as functions of time, market forces, or stochastic variables. The carrying capacity was assumed to grow at 1%, consistent with the human population growth rate of the US (*The World Bank Group*, 2011). Model parameters were assumed to be lumped, deterministic variables reflecting all aspects influencing consumer choice. Five scenarios were investigated to simulate changes in conditions affecting the auto market. A base scenario used current yearly growth rates and current populations of each vehicle class. Other scenarios investigated effects of high oil prices, increased battery performance, government investment, and high electricity rates. Furthermore, an economic analysis was conducted to compare the present day value of two vehicle models currently available. The analysis These results were used to examine the current competitiveness of these vehicles and consider the level of government support that would be adequate to encourage consumer investment in BEVs. Taking into account the time value of money and a discount rate equal to the rate of inflation, the present value of each vehicle was calculated. This analysis showed that without current government subsidies, the Nissan Leaf has lower present value than the Honda Civic and so competes at a fiscal disadvantage against the Civic. A best-case scenario showed that the Leaf is competitive without subsidies. This scenario postulated a linear rise in gas prices to $5 /gallon, increased BEV vehicle efficiency (in kWh/mile driven) and higher resale values due to improving battery technology. The primary weakness of this model is the lack of data available for model calibration and testing. Because so few purely electric vehicles are on the road, and even fewer statistics are available to describe the history of market shares of BEVs, the model could not be calibrated. Refinements of the parameters and growth rates would significantly improve the validity of the model. Unfortunately an analysis of the model's sensitivity to perturbations in its input parameters was not completed due to time constraints.

The scenarios investigated gave long term projections for a shift to BEVs from traditional ICE vehicles. All scenarios predicted an eventual shift but the timing varied significantly depending on the growth rates and the values of the competitiveness parameters. With a significant initial investment to increase the numbers of BEVs on the road, corresponding to an increase in the initial value of $E$ and $H$, the equilibrium point between ICEs and BEVs occurs in the year 2030, compared to the base case of 2035. If coal is expensive and battery prices remain high this point does not occur until 2043. If oil prices rise rapidly, increasing the competitiveness coefficients of BEVs, this point occurs in 2028. When all factors combine to create the best case scenario for BEVs - oil prices are high, battery technology improves, and electricity is comparatively inexpensive- then the model predicts that BEVs, ICEs, and PHEVs would all be present in approximately equal numbers as early as 2027.

| Growth Model | | |
|---|---|---|
| variable | description | units |
| $G(t)$ | number of ICE vehicles | - |
| $E(t)$ | number of BEVs | - |
| $G(t)$ | number of PHEVs | - |
| | | |
| $r_G$ | intrinsic ICE growth rate | 1/year |
| $K_G$ | maximum ICE population | - |
| $\beta_G$ | effect of ICE on BEV | - |
| $\gamma_G$ | effect of ICE on PHEV | - |
| | | |
| $r_E$ | intrinsic BEV growth rate | 1/year |
| $K_E$ | maximum BEV population | - |
| $\alpha_E$ | effect of BEV on ICE | - |
| $\gamma_E$ | effect of BEV on PHEV | - |
| | | |
| $r_H$ | intrinsic PHEV growth rate | 1/year |
| $K_H$ | maximum PHEV population | - |
| $\alpha_H$ | effect of PHEV on ICE | - |
| $\beta_H$ | effect of PHEV on BEV | - |
| **Economic Model** | | |
| $C_0$ | initial capital investment | US $ |
| $L$ | salvage value at end of life cycle | US $ |
| $B_t$ | net benefit after each year | US $ |
| $R_t$ | net cost after each year | US $ |
| | | |
| $I$ | nominal interest rate | % |
| $k$ | compounding period | - |
| $n$ | vehicle life cycle | yr |
| $i_{eff}$ | effective annual interest rate | % |
| $M_c$ | annual maintenance cost | US $ |

Table 0.1: Variables used throughout the model.

# Electric cars as a widespread means of transportation

Exploring impacts on the environment and society using an adapted ecological competition model

ICM Team # 11325

14 February, 2011

# Contents

# List of Tables



# List of Figures

# 1 Introduction

Electric cars have the potential to outperform traditional Internal Combustion Engine (ICE) vehicles, but whereas the effects of driving ICE cars have been well studied, the effects of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) suffer from considerable uncertainty. This report attempts to answer some of the questions surrounding widespread BEV and PHEV use. An ecological competition model is adapted to describe the population dynamics between ICE cars, BEVs and PHEVs. Model results are interpreted using present-day figures of car ownership costs, tailpipe and power plant emissions, electrical generation capacity, job creation and oil consumption. This analysis allows a rough estimate of the greenhouse gas (GHG) emissions, extra electrical demands due to electric vehicle use, and specific measures for manufacturers and governments to speed electric vehicle adoption.

## 1.1 Problem Formulation

Alternative fuel vehicles present possible solutions to pollution and energy problems. The solutions are not simple and using an alternative fuel may not deliver the energy savings or pollution decreases anticipated. BEVs do not use oil, but because most electricity generated in the US comes from coal feedstocks, BEVs do not represent a wholesale movement away from fossil fuels. The environmental impact of coal produced electricity varies by location depending on the infrastructure and applicable emissions regulations. Alternative sources of electricity are possible and research and development of solar, wind, wave and other sources of zero carbon electricity could make an electric car a viable alternative.

Economic considerations are important and similarly complex. Price fluctuations for oil and coal are unavoidable and difficult to predict, varying both regionally and temporally. Additionally, initial costs of new technology are high, but with increased production driving development prices can be expected to decrease. Government support in the early stages of development of new technologies is critical, but cannot be undertaken without research into the viability and marketability of the technology.

Electric cars also have limitations in use that are not seen in internal combustion engines. Current models have fairly short ranges, and little infrastructure exists at this time for recharging in public locations. Both of these factors can be expected to improve as more vehicles are manufactured and commercial operations begin to provide services for BEV owners. Charging time is also a significant consideration. Current estimates indicate a full charge takes approximately five hours (*Perujo and Cuiffo*, 2010). Rapid charging at the electric vehicle equivalent of a filling station would place huge demands on the electrical grid. Alternately, a battery exchange program would allow charging at a slower rate; however, higher initial capital costs would be required to store, maintain and stockpile the batteries. Incentive for potential vehicle owners to buy BEVs would depend strongly on the amount of infrastructure already in place or under construction. Consumers need to know that a new automotive technology has the necessary resources for both convenience and sustainability.

## 1.2 Model Goals

To investigate the viability of a transition to electric vehicles a model was developed to estimate market penetration of electric vehicles under varying conditions. These conditions include the prices and availability of oil and coal, the investment in infrastructure, and the rate of development of battery technology and alternative energy sources. The Lotka-Volterra equations describing interspecies competition were used to simulate the competition between standard ICEs, BEVs, and PHEVs. The estimate of market share was used to calculate changes in $CO_2$ production, oil consumption, and electricity demands. A separate but related economic analysis was also performed comparing the Nissan Leaf and the Honda Civic SI to evaluate the cost to the consumer of each vehicle for an eight year life cycle.

# 2 Methodology

## 2.1 Mathematical Model

The interaction between gasoline, electric, and hybrid vehicles can be represented by a system of ordinary differential equations. The dependant variables in the following model are listed in Table 2.1. $G(t)$, $E(t)$, and $H(t)$ represent the total amount of ICEs, BEVs and PHEVs registered to owners at any time $t$. The initial values for these variables were determined from current data for registered vehicles (*North American Transportation Statistics Database*, 2011).

An ecological approach to competition modeling is represented in the Lotka-Volterra equations (*Wolfram Demonstrations Project*, 2010). This approach considers the effect of multiple species competing for the same resource. The three equations that are used to represent the rates of change in automotive populations are shown in Equations 1, 2, and 3.

$$\frac{dG}{dt} = r_G G \left[1 - \frac{G + \alpha_E E + \alpha_H H}{K_G}\right] \tag{1}$$

$$\frac{dE}{dt} = r_E E \left[1 - \frac{E + \beta_G G + \beta_H H}{K_E}\right] \tag{2}$$

$$\frac{dH}{dt} = r_H H \left[1 - \frac{H + \gamma_E E + \gamma_G G}{K_H}\right] \tag{3}$$

### 2.1.1 Numerical Method

Frequently, a system of ODEs is difficult to solve by hand and a numerical approximation is sought. For equations such as these, computer algorithms that generate numerical solutions within a specified error tolerance are an efficient tool and are favored over tedious analytical efforts (*Chapra and Canale*, 2002).

Table 2.1: Definitions of the dependant variable and the initial conditions.

| variable description | representation | initial condition | source |
|---|---|---|---|
| number of ICE vehicles | $G(t)$ | $G(0) = 246 \times 10^6$ | |
| number of BEVs | $E(t)$ | $E(0) = .01 \times 10^6$ | |
| number of PHEVs | $H(t)$ | $H(0) = .1 \times 10^6$ | |

Table 2.2: Definitions of the parameters used and their units.

| parameter | variable | value | units |
|---|---|---|---|
| intrinsic ICE growth rate | $r_G$ | 1.52 | 1/year |
| maximum ICE population | $K_G$ | 300E6 | vehicles |
| intrinsic BEV growth rate | $r_E$ | 1.52 | 1/year |
| maximum BEV population | $K_E$ | 300E6 | vehicles |
| intrinsic PHEV growth rate | $r_H$ | 1.52 | 1/year |
| maximum PHEV population | $K_H$ | 300E6 | vehicles |
| effect of BEV on ICE | $\alpha_E$ | 1.2 | dimensionless |
| effect of PHEV on ICE | $\alpha_H$ | 1.2 | dimensionless |
| effect of ICE on BEV | $\beta_G$ | 0.7 | dimensionless |
| effect of PHEV on BEV | $\beta_H$ | 1.0 | dimensionless |
| effect of BEV on PHEV | $\gamma_E$ | 0.8 | dimensionless |
| effect of ICE on PHEV | $\gamma_G$ | 1.2 | dimensionless |

The numerical method used to solve the system of ODEs was Runge-Kutta-Fehlberg, using coefficients derived by Cash-Karp. This method minimizes functional evaluations to derive 4$^{\text{th}}$ and 5$^{\text{th}}$ error-order approximations to the solution. The error is estimated to be proportional to ${}^4y_{i+1}$ and ${}^5y_{i+1}$. In the Runge-Kutta-Fehlberg algorithm, the step size $\Delta t$ is adjusted at each iteration to keep the error estimate between upper and lower bounds. This method allows computationally efficient solutions without introducing excessive round-off error due to the finite precision of floating point arithmetic. The Runge-Kutta-Fehlberg method requires one initial value for each DE in the system (*Chapra and Canale*, 2002).

### 2.1.2 Model Calibration

The limited amounts of data available on sales and demand of alternative fuel vehicles, as well as the unpredictability of future costs of oil and electricity make reliable calibration of the model extremely challenging. The model can therefore be best used for running various scenarios and comparing outcomes.

## 2.2 Economic Effects

The cost of fuel (gasoline and electricity) can be represented in the growth model via the competition parameters. As gasoline prices rise, an increasing electric car population has an enhanced effect on the ICE population. If the cost of electricity rises, gasoline engines should be more competitive than BEVs.

The proposed initial infrastructure investment will directly affect the initial conditions of the model. A larger investment in charging or battery swap stations, charging ports in public parking facilities and research to improve technology will result in a greater influx of BEVs at the start of the simulation.

### 2.2.1 Effects of Changing Technology

Battery technology has been improving rapidly. Prices, life cycles, range, and efficiencies of batteries will dictate the strength of the BEV population. Increases in vehicle efficiency through technologies such as regenerative braking, decreased vehicle weight, and more efficient vehicle systems will also reduce operating costs.

### 2.2.2 Present Worth Model

The economic viability of the BEV and the PHEV can be quantified in the present worth method. The EIA forecast gasoline prices and electricity rates were converted to cost per year based on driving an average of 11,720 miles per year (*US Energy Information Agency*, 2010b). This amount was added to average maintenance and repair costs of approximately \$500/year given by *Automotive.com* (2011) to yield a cost per year to operate the vehicle ($R_t$). Equation 4 was used to compute the present value ($PV$) of a nonuniform series of costs (*Willis and Finney*, 2004). With data for the Nissan Leaf and the Honda Civic Si obtained from *Callaway* (2011) and *Penn* (2011), a comparison was made for the cost of purchasing and operating each vehicle for eight years. The model can easily be adjusted for changes in interest rate, resource costs, maintenance costs, driving distance, battery technology, and resale percentage (Equation 4).

$$PV = -C_0 + L[SPPW(i,n)] + \sum_{t=1}^{n} \frac{B_t - R_t}{(1+i)^t} \tag{4}$$

where

$$i = i_{eff} = \left(1 + \tfrac{I}{k}\right)^k - 1$$

### 2.2.3 Effects on the Environment

Though the cost per kWh for electricity is low compared to fuel prices in a miles per dollar comparison, conservation of electricity will be essential. Using figures from *Perujo and Cuiffo* (2010), the potential power demand of 100,000 electric vehicles charging simultaneously is calculated to be 440 GW. If the charging cycle were not regulated, and coincided with the peak demand, electricity suppliers would have to build extra generation capacity to meet the additional demand. Considering that a typical coal-fired generator has a capacity of 236 MW of power (*US Energy Information Agency*, 2009), this influx of electricity demanding vehicles would require an additional 1,865 generators or their equivalents.

#### 2.2.4 Renewable Energy

The availability of renewable energy resources needs to be fully exploited to accommodate a large spike in electricity consumption. The type and amount of non fossil fuel energy available varies by region, but maximum exploitation of these sources will significantly reduce pollution.

#### 2.2.5 Effects on Society

Social benefits can be quantified in terms of jobs. More production facilities, research positions, construction of infrastructure, vehicle design and maintenance will be needed. The Political Economy Research Institute estimates that 18,000 jobs are created for every billion dollars spent on infrastructure, including direct and indirect employment (*Heintz et al.*, 2010).

#### 2.2.6 Effects on Human Health

In this model, potential health risks are determined from the amount of pollutants emitted from vehicles when driven, including tailpipe emissions and emissions from coal fired power plants. Health risks associated with $NO_x$, $SO_x$, and particulate matter can be represented monetarily. Health risks per ICE have been estimated to cost $103 per vehicle annually from particulate matter (*Guo et al.*, 2010). These costs are incurred as a result of assigning monetary values to premature deaths and increased illness rates associated with particulate pollution levels from cars.

# 3 Results

As represented in Equations 1–3, the behavior of $G$, $E$, and $H$ is mostly controlled by the value of the interspecific competition coefficients. Model parameters were matched to the best available data describing growth rates of PHEVs, BEVs and ICEs, their relative competitiveness and the total number of registered cars. To describe the competition between BEVs and ICEs, the economic model predicted the BEV has a competitive edge against the ICE. The PHEV was assumed to be described by a competition factor of equal value.

## 3.1 Economics of current BEVs vs. ICEs

A 2003 Honda Civic sold for an average of $16,680 (*HowStuffWorks.com*, 2011) and a current good condition trade in value after 8 years and 100k miles is about \$4,000 (*Kelley Blue Book*, 2011). This is an average resale value of 24%. However, this does not factor in the time value of money. Multiplying the 2003 MSRP by the Single Payment Compound Amount, $SPCA = (1+i)^n$, factor, with a nominal interest rate ($I$) of 2% compounded monthly ($k = 12$), the present value is \$19,571. which is a resale value of about 20%. Assuming a similar resale value, the 8 year, 100k mile salvage value ($L$) of a 2011 Honda Civic is : $MSRP \times 20\% = 22,405 \times 0.2 =$ \$4,551. With these values, $PV =$ \$33,487.

Lack of long term data on electric vehicles made estimating salvage values for the Nissan Leaf difficult. If the maintenance costs and resale values are assumed to be equivalent to the Civic an initial comparison can be made strictly on the cost of fuel and capital costs. For the Leaf, with a MSRP of \$32,780, an incentive tax credit of \$7,500 (*Penn*, 2011), and an eight year salvage value of \$6,556, $PV =$ \$27,803, \$5,684 less than the Civic. Since it is not yet possible to determine the resale value of a BEV or its battery, sensitivity to these model inputs is useful. Table 3.1 presents a sensitivity analysis of the economic model.

Table 3.1: The economic model's sensitivity to changes in interest rates, salvage value, efficiency and maintenance costs.

**Percent Change**

| Leaf | Civic | Cost differential |
|---|---|---|
| $L \pm 5\%$ | - | $\mp$ 24.3% |
| - | $L + 5\%$ | $-16.0\%$ |
| - | $L - 5\%$ | +18.0% |
| $M_c \pm 20\%$ | - | $\mp$ 12.7% |
| - | $M_c \pm 20\%$ | $\pm$ 12.7% |
| \$/kWh $\pm 5\%$ | - | $\mp$ 2.0% |
| kWh/km $-5\%$ | - | + 3.9% |
| - | \$/gal $\pm 5\%$ | $\pm$ 9.8% |
| $i + 3$ | $i + 3$ | − 26.3% |

## 3.2 Population Model Results

As a comparison across several future scenarios, the time at which $G$ is equal to $E$ was used. Because the populations of vehicles span several orders of magnitude over the model time period, a semi-log scale is used to display the results.

### 3.2.1 Base Scenario

As a base case, the BEV and PHEV were presumed to be more competitive than the ICE vehicle. The projected increase in battery technology, combined with rising oil prices led this assumption. Further evidence of the BEV's competitive advantage in the market is given by the economic analysis of the Nissan

Leaf against the Honda Civic (Section 3.1). For the base case, the model parameters are those in Table 2.2. Results are given in Figure 3.1; $G$ and $E$ are equal in 2035.

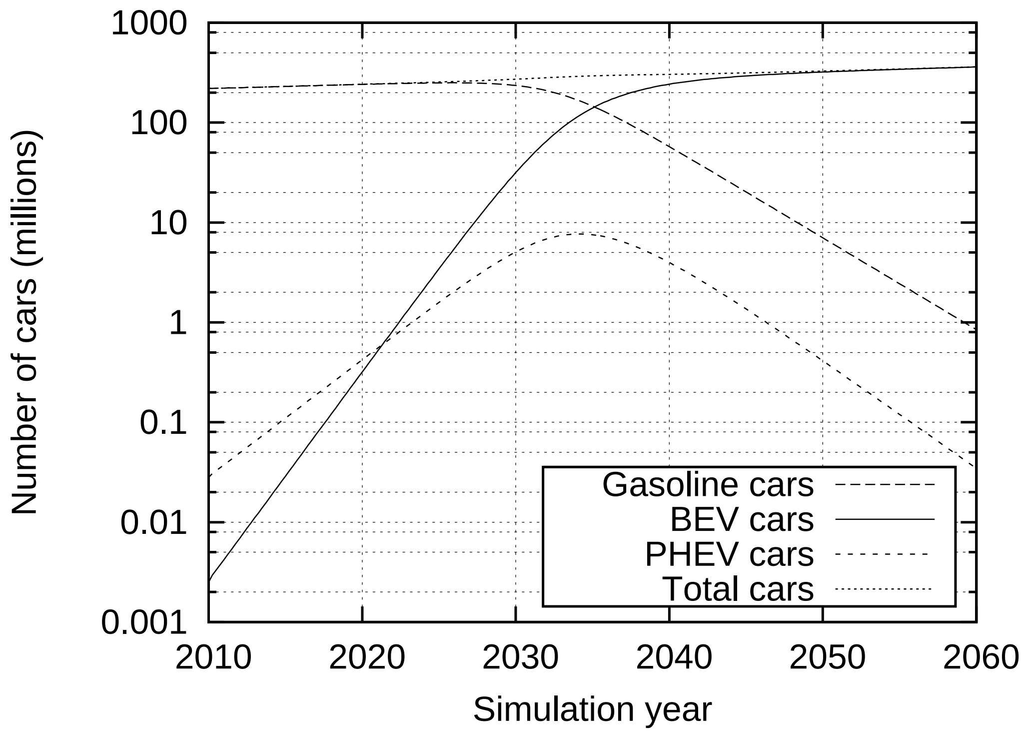


Figure 3.1: Base scenario. The BEV enters the market with a competitive advantage over the PHEVs and ICE cars, but the low initial market penetration hinders the speed at which they overtake the number of ICE cars on the road.

### 3.2.2 Scenario 1: Heavy investment in electric vehicles

Additional investment will permit a larger initial BEV and PHEV population. This investment is assumed consist of measures that:

- Support converting ICE manufacturing plants to produce BEVs and PHEVs
- Encourage consumers to purchase BEVs and PHEVs instead of ICEs
- Support infrastructure development such as electrical grid improvements and charging stations
- Promote research into improving battery capacity and reducing battery cost
- Incentivize zero carbon electricity generation capacity

These measures are assumed to effect a tenfold increase in initial BEVs and PHEVs populations in 2010. This change moves the ICE and BEV equilibrium point forward ten years with respect to the base scenario: $G$ and $E$ are equal in 2025 (Figure 3.1).

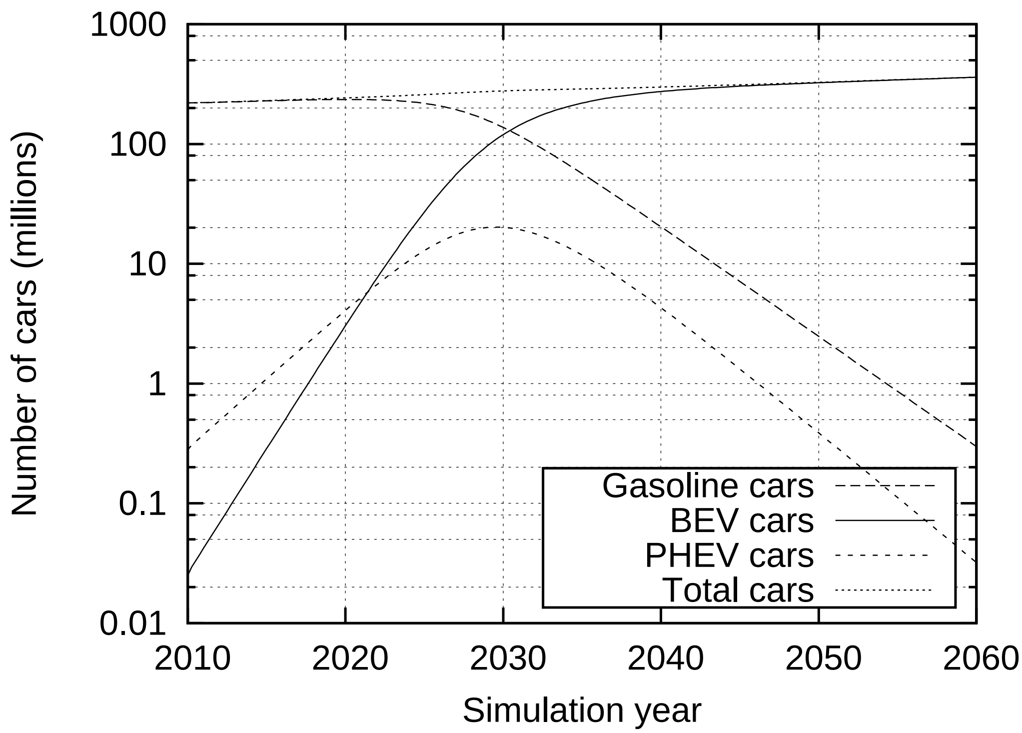


Figure 3.2: Scenario 1. Additional infrastructure stimulates accelerated adoption of the BEV and PHEV, making their initial populations ten times larger than the base case.

### 3.2.3 Scenario 2: Electricity becomes more expensive

In the event that electricity becomes much more expensive, growth of BEVs would be hindered. PHEVs may still be able to hold a market share but battery performance will dictate to what degree. For this analysis, battery technology is assumed to improve slowly, while the price of oil continues to climb. Eventually the BEV becomes competitive and overtakes ICE vehicles. However, the timing of the equivalence point timing is retarded with respect to the base case (Figure 3.3). $G$ equals $E$ in 2042.

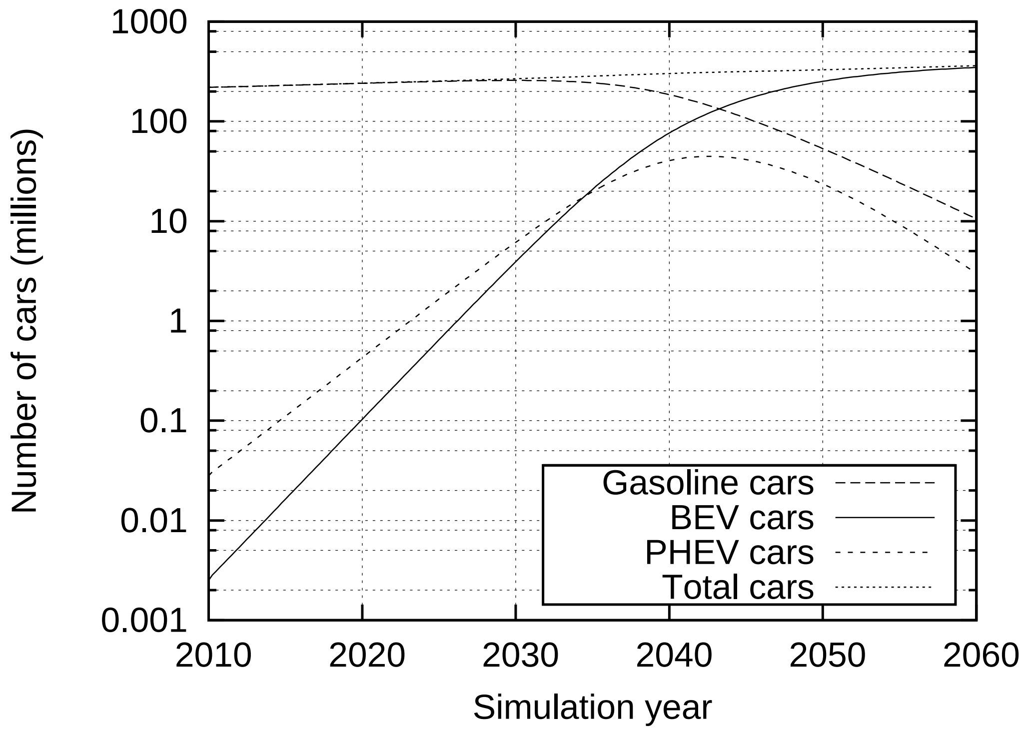


Figure 3.3: Scenario 2. The BEV and PHEVs enter the market with a competitive advantage over ICE cars, but this advantage is tempered by high electricity rates. The equivalence point is delayed by several years, to 2042.

In this scenario, PHEVs enjoy a decided market advantage over BEVs until oil prices rise too high. The increased price of driving the PHEV then causes a slide in the competitiveness against the purely electric powered BEV. To accomplish this change in the model the intrinsic growth rate of the BEV, $r_E$, was decreased to 1.2, or a 20% year over year. This simulates the reluctance of customers to purchase a vehicle with high per-mile costs.

### 3.2.4 Scenario 3: Oil prices rise

This scenario assumes oil prices rise and stay high throughout the modeling period. The increased cost to operate the ICE is reflected in decreased competitiveness factors against the BEV and PHEV. $\alpha_E$ and $\alpha_B$ were both increased to 1.3, while $\beta_H$ was decreased to 0.6 and $\gamma_G$ was decreased to 0.7. These measures were to simulate the penalties the fossil fuel burning vehicles face against a purely electric BEV. The equivalence point occurred in 2028, only three years after the equivalence point in the base scenario.

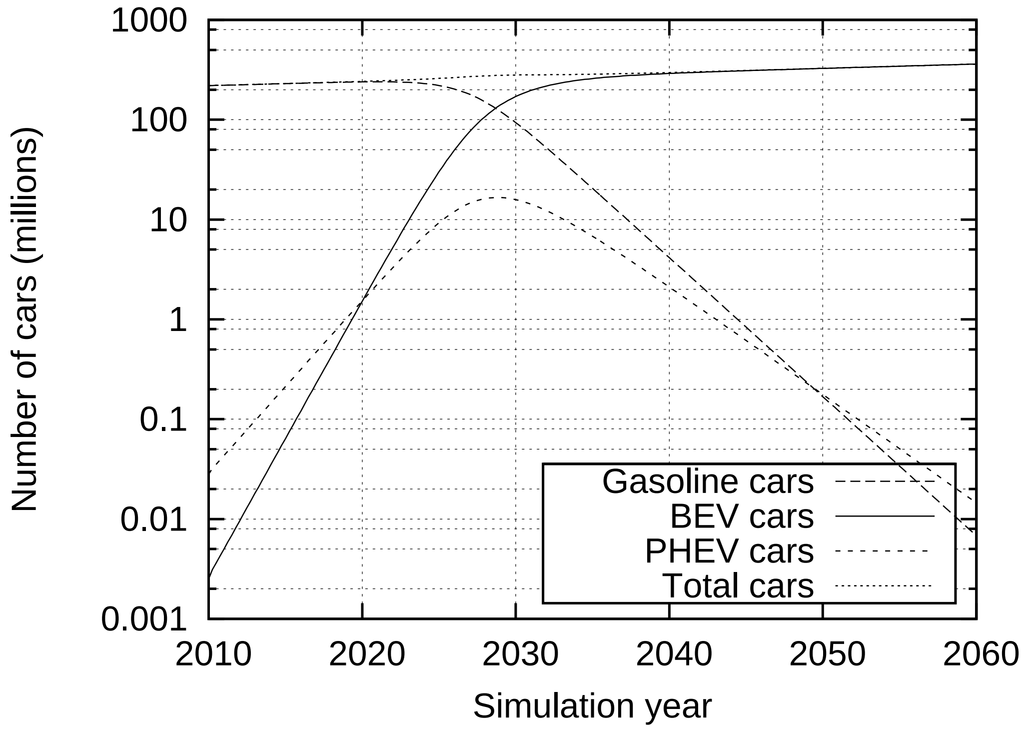


Figure 3.4: Scenario 3. The BEV and PHEVs enter the market with a competitive advantage over ICE cars. This advantage is increased due to high oil prices.

#### 3.2.5 Scenario 4: Best case for BEVs

For a best case scenario, Scenarios 1 and 3 were combined and advancements in battery technology were incorporated. This case produced an equilibrium point in 2018 (Figure 3.5).

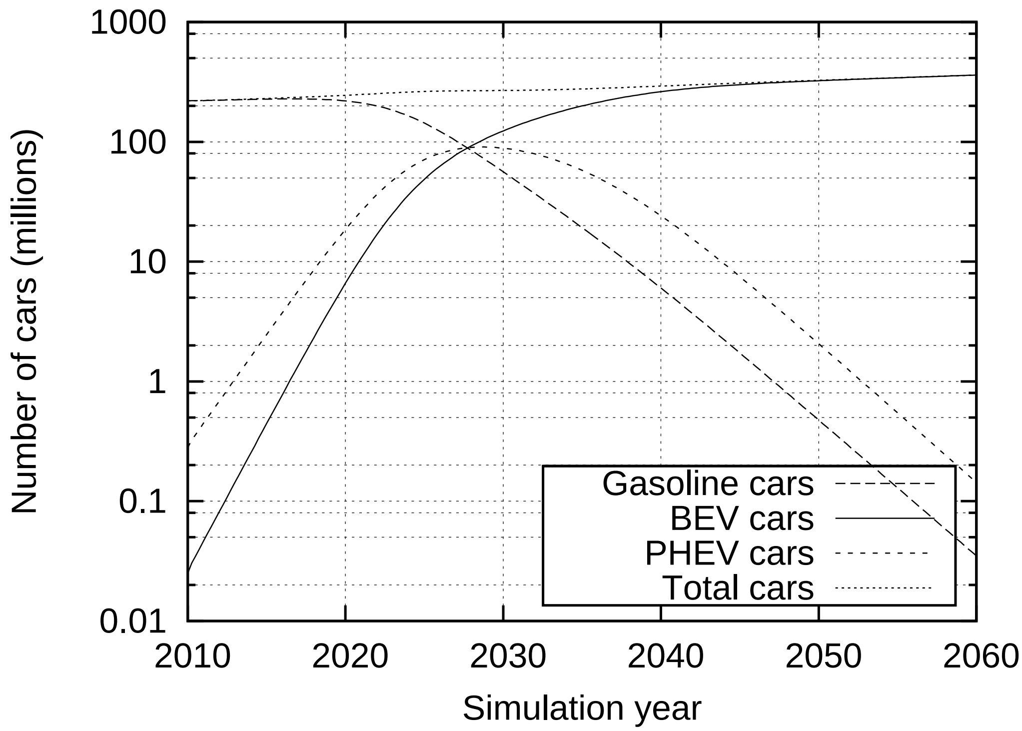


Figure 3.5: Scenario 4. The BEV and PHEVs enter the market with a competitive advantage over ICE cars. This advantage is heightened by early infrastructure investment, cheap battery technology and high oil prices. Both PHEVs and BEVs are adopted early, but the BEV ultimately dominates the market due to reliance on non-petroleum energy sources.

## 3.3 Emissions

Widespread adoption of the electric car did not reduce emissions of all pollutants; although the emission rates of some pollutants appeared to be driven by economic growth irrespective of the vehicle choice. While electric vehicles do not have tailpipe emissions particulate matter from coal burning can increase tenfold from the gasoline engine (*Argonne National Laboratories*, 2011)

#### 3.3.1 Airborne pollutants

While widespread use of the electric car is expected to reduce emissions in cities and in dense population centers, the overall effect on emissions was mixed. Using data from the GREET model (*Argonne National Laboratories*, 2011) and assuming a power generation mix of the present-day US, emissions of various pollutants were found to change over the modeled period as shown in Table 3.2.

Table 3.2: Change in emissions over the period 2010-2060 in the base scenario.

| **Pollutant** | **Change** | **Pollutant** | **Change** |
|---|---|---|---|
| $CH_4$ | +39% | $N_2O$ | -64% |
| GHGs | +24% | VOCs | -84% |
| CO | -87% | $NO_x$ | +94% |
| $PM_{10}$ | +940% | $PM_{2.5}$ | +580% |
| $SO_x$ | +860% | | |

Data from *Argonne National Laboratories* (2011) was used to describe total emissions produced per mile driven of each type of vehicle. Although the model predicted a tenfold increase in $PM_{2.5}$ and $PM_{10}$ when electric vehicles became widespread, the model was not designed to describe the spatial distribution of particulate pollution. Higher concentration of particulate pollution emitted from power plants in areas with low population density may have a less costly effect than the relatively low particulate pollution density emitted at ICE tailpipes in much more densely populated areas. The scrubbers and other emissions equipment added to new generation equipment may cause the overall emissions distribution from electric generators to decline over time. The estimates in Table 3.2 do not take these changes into account.

### 3.3.2 $CO_2$

Using information from *Environmental Protection Agency* (2011), the data from each scenario were analyzed to predict $CO_2$ emissions attributable to the transportation sector. As shown in Figure 3.6, the greatest reduction in $CO_2$ production corresponded to bringing the more energy efficient PHEVs and BEVs to market dominance the fastest. The worst case scenario modeled led to a drop in $CO_2$ emissions, but on a significantly lagged timescale. The rising trend evident in the left and right hand sides of the curve reflect assumptions about the growth rate of the number of registered vehicles. Because the $CO_2$ emissions of BEVs and PHEVs occur at power generation facilities rather than at the vehicle tailpipe, a growing population of BEVs and PHEVs will still cause higher emissions. However, because their energy efficiency is higher than ICEs, substantial carbon savings can be realized by switching to electric vehicles. Generating a greater proportion of the nation's electricity from non-carbon sources, such as nuclear or wind, will allow further reductions in carbon produced by electric vehicles.

## 3.4 Oil consumption

Important considerations driving interest and investment into electric vehicles are the effects of importing the vast majority of oil needed to fuel the grow-

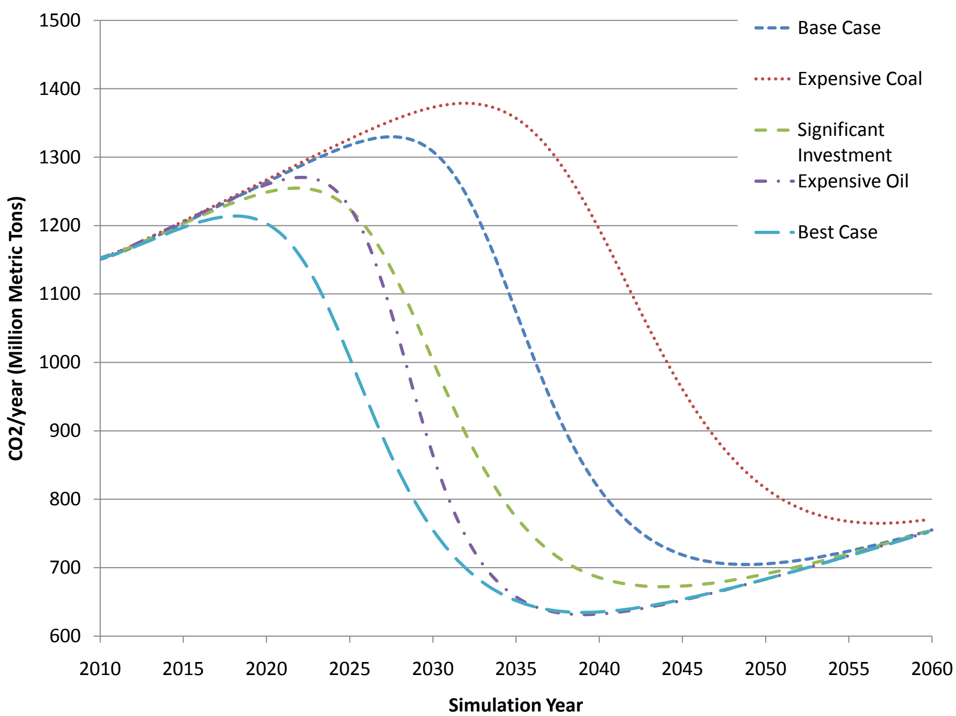


Figure 3.6: $CO_2$ production drops as the BEV begins to dominate the market. Advancing the competitiveness of the BEV and PHEV leads to the greatest reductions in $CO_2$ by the transportation sector.

ing transportation sector. Because the transportation sector consumes roughly three quarters of the US oil supply (*US Energy Information Agency*, 2010b), oil consumption will not be eliminated entirely, but may be significantly reduced.

## 3.5 Electricity Demand

The US consumed 3,950 million MWh of electricity in 2009 (*US Energy Information Agency*, 2011). The greatest additional electrical demand projected by the model was 1,040 million MWh (Figure 3.8) in 2060. This demand is due to the need to charge the electric vehicle between trips. Although infrastructure improvements may be required to supply the added demand, the electrical grid appears capable of meeting the increase in demand due to the charging needs of electric vehicles.

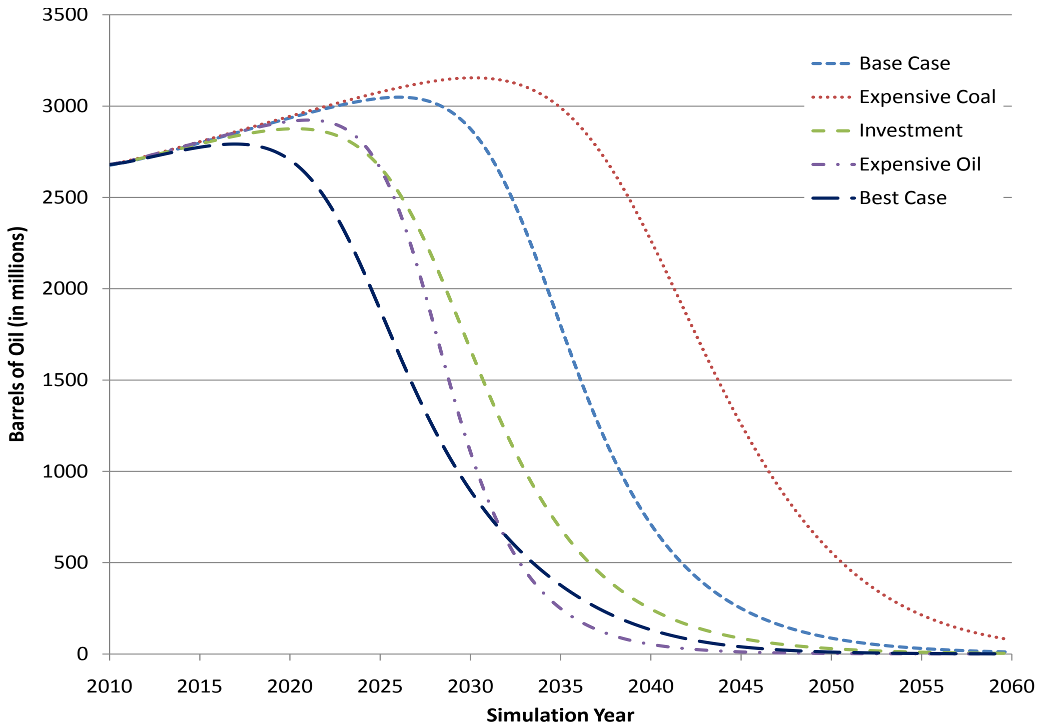


Figure 3.7: Consumption of oil by the transportation sector drops at a faster rate the quicker the electric car gains market share.

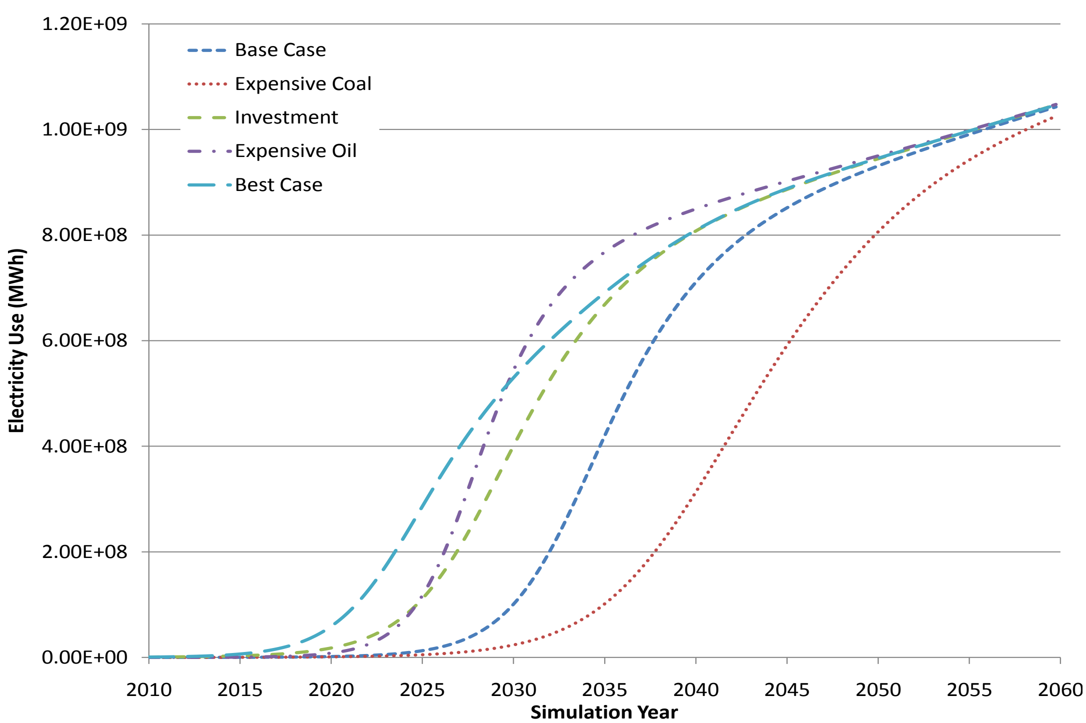


Figure 3.8: The added electrical burden due to charging BEVs and PHEVs will require several billion MWh of electricity to be produced.

# 4 Discussion

## 4.1 Model Parameters

The parameters $\alpha$, $\beta$, and $\gamma$, as well as the initial conditions and the $K$ values will all be region specific. Once data is collected on the amount of BEV impact on the sales and operation of gasoline vehicles, these parameters can be estimated more accurately. The values of $r_G$, $r_E$, and $r_H$ are the growth rates for the various types of vehicles. The numbers used for the base case are based on current trends and were assumed constant. In reality, these rates will be functions of supply and demand and could change dramatically with time.

## 4.2 Demand

The demand for BEVs will be restricted by range and infrastructure. Current buyers would likely be urban commuters, who may also own another vehicle for use on longer trips. Improvements in infrastructure allowing charging or battery exchange at public locations would increase the appeal to individuals who require one vehicle for all purposes.

## 4.3 Power Supply

The demand on electricity could potentially be unmanageable. The model predicts increased annual electricity demands of more than a billion MWh over 50 years regardless of the scenario (Figure 3.8). This increased demand reflects an almost complete switch to electric vehicles. Half of this increase could occur in less than 20 years in the "best case" scenario. To avoid a power supply shortage, additional electricity generation and conservation will almost certainly be necessary. Certain technologies have the potential to reduce the demand or change the timing of charging to reduce the need for extra generation capacity. Encouraging off peak charging would reduce the need for additional power generation. Smart devices that delay charging to off peak hours regardless of when consumers plug in could decrease the need for additional power sources as well as the cost of operation for the consumer (*Perujo and Cuiffo*, 2010). Further improvements to battery technology could increase the battery energy density while decreasing the battery mass. This in turn would lead to increased energy efficiency (in kWh/mile driven by BEVs), thus lowering charging demands. Other technology could utilize the electric storage of the grid-connected electric vehicles to provide extra capacity without building generation plants (*Perujo and Cuiffo*, 2010).

Commercial operations that provide day-time charging from renewable sources could also reduce the impact on existing supplies while reducing the carbon emissions from electric vehicles. Businesses could provide free charging while customers shop as a marketing strategy. Battery exchanges at service stations may yield better results for public charging than rapid charging due to the power demands of rapid charging. Low interest loans to cities to provide metered parking spaces with alternative power supplies could provide infrastructure. Simply generating more electricity from the prototypical coal-fired power plant and increasing grid capacity will have environmental consequences beyond the savings from reduced ICE emissions. However, estimates by *Perujo and Cuiffo* (2010) indicate the BEV's superior energy efficiency would still offset the production of electricity from high carbon sources. Furthermore, predictions by *US Energy Information Agency* indicate the proportion of electricity generated by coal will steadily decrease (2010a). This trend would decrease transportation sector-related $CO_2$ emissions by an even greater margin than that provided merely by the switch to electric vehicles.

## 4.4 Health

Health impacts are difficult to quantify, but have both social and economic impacts. Healthcare costs have been estimated at $103 per vehicle driven (*Guo et al.*, 2010). These costs were estimated based on tailpipe emissions. BEVs have zero tailpipe emissions but increase emissions from power generation. While electric vehicles represent an overall decrease in $CO_2$ and other harmful pollutants, it is important to note that they also relocate the emissions from congested urban areas to the rural and industrial locations of power plants.

## 4.5 Environment and Pollution

Predictions of peak $CO_2$ production range from approximately 1200 to 1400 million metric tonnes per year (Figure 3.6) from transportation. Since BEVs have lower $CO_2$ production the amount produced depends on the number of ICEs replaced by BEVs. This is an improvement and BEVs can be part of a comprehensive energy solution, but must go hand in hand with development of renewable energy sources. Developing BEVs without developing renewable energy sources may slow the rate of climate change, but will not provide a permanent solution.

## 4.6 Oil Consumption

Just as the model predicts increasing electricity demand as more BEVs are on the road it predicts declining oil usage from transportation. Figure 3.7 shows the expected oil demand under all scenarios as electric vehicles replace gasoline automobiles. In the model the decline of oil consumption is strongly dependent on the $\alpha_E$ and $\alpha_H$. Ideally, all competition variables should be functions of the prices of the vehicles respective fuels.

## 4.7 Economics

The results from Table 3.1 divulge useful information on the economic feasibility of electric cars. The largest effect is seen from the salvage value for the Nissan Leaf. The actual value of the car and its battery after the 8 year warranty are not yet known but the model could be updated as data is collected. An important factor to consider is the The $7500 tax credit for buying the Leaf which fits with Scenario 1. To overcome this incentive and make the two cars equal in overall cost, the resale value of the Leaf would need to be 26%, or 6% higher than the Civic. However, over the the eight year lifespan of the vehicles, technology is expected to improve and resource costs are going to vary.

Scenario 2 considers a rise in electricity costs along with rising oil prices. Since gasoline engines require more fuel per mile, the rising costs of oil have a larger effect on the cost differential. Even with electricity rates ($/kWh) increasing 10% from the predicted rates, the Leaf still costs $5500 less than the Civic. If the rate increase and the increase in vehicle efficiency (kWh/km) are both considered, the cost differential in Scenario 2 is equal to Scenario 1. However, if the tax credit is removed, only a 33% increase in BEV efficiency coupled with a 10% decrease in electricity and a 10% increase in gas prices would make the cost two cars approximately equal.

The degree to which technology will improve the efficiency of electric vehicles also remains to be seen. Scenario 3 assumes the status quo in BEV technology but incorporates higher oil prices alone. If gasoline were to become $5/gal in eight years and increase linearly, The Leaf would be $8438 cheaper than the Civic, a 47% increase in cost differential. This is more than enough to overcome the need for a tax credit to make the BEV competitive.

The best case, Scenario 4, includes rising gasoline prices with improved technology and initial investments. This increases the car and battery resale value, the BEV efficiency, and the cost of gasoline. Keeping the tax credit in place, the consumer would save $10,585 by purchasing a Leaf over a Civic. Without the tax credit, the differential is still $3,085. Though this situation is optimistic, it is not unreasonable.

There are many factors unaccounted for in the economic model but the effect that certain changes will have can be predicted. With very little data to use for BEVs comparison in future costs may not have validity in pure dollar amount but the change in costs and an overall cost comparison indicate realistic behaviors. The interest rate used is also a significant factor since a change from 2% to 5% changed the cost differential by 26%. The true value for the nominal interest rate to use in the model would need to be determined accurately.

## 4.8 Government Support

The role of government in supporting new technology has a great impact on the degree of market penetration. Early subsidies that increase the number of vehicles on the road have a large effect on model results. This is due to predictions based on percentage growth rates, and assumes that the number of cars produced in a given year depends on the number already on the road. In a practical sense this should be applicable since familiarity increases consumer willingness to purchase the vehicles. A larger number of vehicles on the road also spurs investment in supporting infrastructure as commercial interests recognize a new market. Government support for research and development to speed technology improvements in battery efficiency, vehicle range and cost could improve market penetration as well as decrease the electricity demand per vehicle.

# 5 Conclusions

The electric car offers many benefits over the internal combustion-powered car. Chief among these factors is its higher energy efficiency. To compete with the ICE, however, battery technology improvements and infrastructure investment is needed to boost market growth. The analysis presented here shows the savings in $CO_2$ and oil become greater the faster the electric car is able to dominate the market. The rate at which the BEV are able to overtake ICEs was determined to be a factor of advanced technology, infrastructure investment, and government incentives.

Economic analysis of the Nissan Leaf against a conventional Honda Civic indicates subsidies are currently needed to make the Leaf competitive against the Civic. As battery technology and charging infrastructure improve, the BEV is expected to improve its competitiveness against the ICE. In the event gasoline prices hit $5/gal in 2019, the cost of owning and operating a Leaf would be thousands less than a Civic

The model suffers from considerable uncertainty. Because data for BEV performance and durability over time is not yet available, preliminary simulation may not provide accurate predictions. However, it is believed that the behavior of both the growth and the economic model can represent realistic trends. As data becomes available, the parameters can be calibrated and the model can be verified. The scenarios considered in these models can also relate changes in economic conditions to to the feasibility of sustaining an electric vehicle market.

## 5.1 Recommendations for further study related to this model

- Incorporate expected changes in vehicle technology and emissions standards into the growth model parameters
- Couple the economic model with the growth model to predict present values of future trends
- Calibrate the model using market and performance data as they become available
- Introduce stochastic variation to describe more realistic charging periods and energy demand

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