

Economic and Environmental Optimization of Vehicle Fleets

Impact of Policy, Market, Utilization, and Technological Factors

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This paper focuses on the economic and environmental optimization of decisions about vehicle replacement from a fleet manager's perspective. An integer programming vehicle replacement model is used to evaluate environmental and policy issues such as greenhouse gas (GHG) taxes and fiscal incentives for purchasing electric vehicles (EVs). This research also analyzes the impacts of utilization (mileage per year per vehicle) and gasoline prices on vehicle-purchasing decisions. Energy and emissions reductions for a variety of scenarios using real-world data in the United States are presented as well as break-even points at which EVs are competitive. Findings include the following: (a) fuel-efficient vehicles such as hybrids and EVs are purchased only in scenarios with high gasoline prices or high utilization, (b) current European carbon dioxide cap-and-trade emissions price (around \$18.70/ton) does not significantly alter fleet management decisions, and (c) incentives for using EVs (i.e., tax credits) increase the rate of purchase of hybrid and electric vehicles in scenarios with high gasoline prices and high vehicle utilization. This research indicates that the proposed model can be used effectively to inform environmental and fiscal policies on vehicle regulations, tax incentives, and GHG emissions.

The recent volatility of fossil fuel prices and growing concern about the environmental costs of fossil fuel production have drawn attention to the need to reduce energy consumption and diversify into cleaner energy sources. Simultaneously, vehicle technologies are rapidly evolving and the automobile market is changing accordingly. In particular, electric vehicle (EV) technology is considered by many environmental advocates as a promising solution to reduce fossil fuel consumption and greenhouse gas (GHG) emissions (1). This research uses the following conventions to denote different types of vehicles and engine technologies. Internal combustion engine vehicles, also called conventional vehicles, use gasoline or a fossil fuel as the only source of energy. Hybrid electric vehicles (HEVs) have an internal combustion engine in addition to a battery that can be used to power the vehicle wheels. Plug-in-hybrid electric vehicles (PHEVs) are similar to HEVs but usually have a battery with higher capacity. PHEVs can also be plugged in to the electrical grid—hence, the PHEV battery is mostly recharged by the grid whereas the HEV battery is recharged when the vehicle brakes or decelerates. EVs have an electric engine and no combustion engine.

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Although still a small share of the automobile marketplace, hybrid vehicle models and sales have been growing steadily. It is now possible to buy several types of HEVs such as the Toyota Prius, Honda Civic, and Ford Escape. Even luxury brands such as Lexus and Porsche are working on sporty hybrid vehicles (2). As of October 2010, Mitsubishi launched the i-MiEV in Japan (April 2010) and several carmakers are about to release into the market new EV or PHEV models; for example, the Nissan EV Leaf (December 2010) and the Toyota PHEV Prius (2012) (3). An intermediate alternative between EVs and conventional vehicles is the Chevrolet Volt, which can be powered by an electric motor for 40 mi and has a battery that can be recharged by an internal combustion engine or at a charging station.

Economic conditions are also changing rapidly. After the growth and expansion observed in the middle of the past decade, the economic crisis that started in late 2007 is limiting consumers' disposable income and access to credit. At the fleet level, private companies and state agencies have been forced to adopt comprehensive planning approaches that seek to reduce operating costs, maintain customers' service levels, and—when possible—continue sustainable practices or cap GHG emissions.

Decision makers are faced with complex trade-offs involving economic, environmental, and policy impacts of fleet management decisions and regulations. This research aims to provide a better understanding of the monetary, emissions, and energy consumption trade-offs associated with distinct vehicle technologies (conventional fossil fuel, hybrid, and electric) using current real-world market and efficiency data. Specific contributions of this research include incorporating GHG costs into fleet vehicle replacement-type models, analyzing the competitiveness of current engine technologies in the United States, and evaluating the impacts of policies (tax credits, GHG taxes), usage (miles per year), and market conditions (fuel prices) on the competitiveness of EVs.

This paper is organized as follows. The next section presents a literature review. The third section introduces the notation and formulation of the fleet management model used in the research. The fourth section describes the base case scenario and 15 alternative scenarios used to study the trade-offs among technologies, GHG costs, fiscal policies, and fuel prices. The fifth section describes data sources and model inputs. The sixth section highlights key results and the final section presents conclusions.

LITERATURE AND DATA REVIEW

Because GHG emissions largely depend on the level of consumption of the available forms of gasoline or diesel fuels, private companies have natural economic incentives to use vehicles that are more fuel

efficient or are powered by less expensive and cleaner energy sources. Incentives to use greener technologies may be compounded by government incentives (e.g., a cash for clunkers program and tax breaks for new EVs). However, more energy-efficient PHEVs and EVs have higher upfront purchase prices than conventional gasoline engines in the same vehicle class. For example, a Nissan Leaf has a purchase price of \$33,720, whereas a similar-sized conventional Ford Fiesta has a purchase price around \$13,200 (4). In addition, as a vehicle ages, its value depreciates and operating and maintenance costs tend to increase. Depreciation and maintenance costs depend on the vehicle and engine type as well as utilization and maintenance policies.

Management science and operations research literature pioneered the use of vehicle replacement models (VRMs) to optimize decisions about vehicle purchases, scrapping, maintenance, and utilization. A formal optimization model dealing with a similar, but more general, topic of equipment replacement models was introduced in the 1950s (5). Another important development was the addition of parallel replacement models in which management decisions are made for a set of machines or vehicles instead of one machine or vehicle at a time (6). Although the machine and vehicle replacement literature is rich in models dealing with budget constraints (7), variable utilization (8), stochastic demands (9), and heterogeneous vehicle types (10), these models have not been used to evaluate environmental impacts or government policies.

Despite modeling advances in VRMs since the 1950s, scant attention has been given in the fleet replacement literature to fleet costs associated with emissions and energy sources. Some researchers used averages or simpler economic models to evaluate the benefits of early EVs or HEVs over conventional vehicles. For example, Deluchi et al. analyzed the technological challenges, life-cycle costs, and environmental advantages of EVs (11). They concluded their analysis in a cautiously optimistic note, indicating "Thus, by the turn of the century, EVs could be viable second cars in multicar households." Other researchers concluded that the hybrid Toyota Prius was not cost-effective in improving fuel economy or lowering emissions compared with a conventional Toyota Corolla (12).

Other lines of research have focused on statistical analyses of fleet data and the relationships among age, utilization, and costs (13–15). Another group of researchers has focused on general life-cycle optimization of vehicle replacement decisions (16, 17); however, these approaches cannot be applied directly to a specific fleet because they were intended for policy planning purposes. These life-cycle models are not useful for a fleet manager because they do not provide requisite answers about when and what to purchase, replace, or scrap over time as a function of cost and utilization. Although this type of research can provide useful insights about the general timing of scrapping decisions or the probability of vehicle breakdown, it cannot be used to forecast or analyze the competitiveness of new technologies or vehicle types.

To the best of the authors' knowledge, there is no published research that simultaneously incorporates the impacts of new engine technologies, GHG costs, fiscal policies, and market conditions into fleet management models, as is done in this paper for 2010 passenger vehicle technologies in the United States.

DECISION MODEL

The fleet replacement model described in this section aims to provide answers about when and what to purchase or replace or to salvage or scrap over time as a function of cost and utilization. The goal is to present a model that is parsimonious yet can evaluate the impacts

of new engine technologies, GHG costs, fiscal policies, and market conditions. The VRM used in this paper is an extension of the work of Hartman but also incorporates multiple vehicle types and GHG emissions costs associated with vehicle utilization and production costs (10).

For readability and easy interpretation of the model, decision variables or the cardinality of a set are denoted as capital letters, sets are denoted by bold capital letters, and parameters are denoted by using small letters in four categories: constraints, cost or revenue, emissions, and initial conditions.

MODEL FORMULATION

Indexes

- Age of vehicle type k in years: $i \in \mathbf{A}_k = \{0, 1, 2, \dots, A_k\}$;
- Time period decisions, made at the end of each year: $j \in \mathbf{T} = \{0, 1, 2, \dots, T\}$; and
- Type of vehicle or engine: $k \in \mathbf{K} = \{1, 2, \dots, K\}$.

Decision Variables

- X_{ijk} = number of i -year-old, k -type vehicles in use from end of year j to end of year $j + 1$;
- Y_{ijk} = number of i -year-old, k -type vehicles salvaged at end of year j ; and
- P_{jk} = number of k -type vehicles purchased at end of year j .

Parameters

Constraints

- $a_k = A_k$ = maximum age of vehicle type k (it must be salvaged when it reaches this age),
- u_{ijk} = utilization (miles traveled by an i -year-old, k -type vehicle from end of year j to end of year $j + 1$),
- d_j = demand (miles traveled by all types of vehicle) from end of year j to end of year $j + 1$, and
- b_j = budget (available for purchasing new vehicles) constraint from end of year j .

Cost or Revenue

- v_{jk} = cost of a k -type vehicle purchased at end of year j ;
- om_{ik} = operation and maintenance cost per mile for an i -year-old, k -type vehicle;
- s_{ik} = salvage revenue (negative cost) from selling an i -year-old, k -type vehicle;
- ec = emissions cost per ton of GHG; and
- dr_j = discount rate, value of money over time.

Emissions

- ep_k = production emissions, in GHG equivalent tons, associated with a k -type vehicle;
- es_k = scrapping emissions, in GHG equivalent tons, associated with a k -type vehicle; and
- em_{ik} = utilization emissions in GHG equivalent tons per mile for an i -year-old, k -type vehicle.

Initial Conditions

h_{ik} = number of i -year old, k -type vehicles available at time 0.

Objective function

$$\begin{aligned} \text{minimize} \quad & \sum_{j=0}^{T-1} \sum_{k=1}^K (v_{jk} + \text{ep}_k \text{ec}) P_{jk} (1 + \text{dr}_j)^{-j} \\ & + \sum_{i=0}^{N_k-1} \sum_{j=0}^{T-1} \sum_{k=1}^K \text{om}_{ik} u_{ijk} X_{ijk} (1 + \text{dr}_j)^{-j} - \sum_{i=1}^{N_k} \sum_{j=0}^T \sum_{k=1}^K (s_{ik} - \text{es}_k \text{ec}) Y_{ijk} (1 + \text{dr}_j)^{-j} \\ & + \sum_{i=0}^{N_k-1} \sum_{j=0}^{T-1} \sum_{k=1}^K \text{em}_{ik} u_{ijk} \text{ec} X_{ijk} (1 + \text{dr}_j)^{-j} \end{aligned} \quad (1)$$

subject to

$$\sum_{k=1}^K v_{jk} - P_{jk} \geq b_j \quad \forall j \in \{0, 1, 2, \dots, T-1\} \quad (2)$$

$$\sum_{i=0}^{N_k-1} \sum_{k=1}^K X_{ijk} u_{ijk} \geq d_j \quad \forall j \in \{0, 1, 2, \dots, T-1\} \quad (3)$$

$$P_{jk} = X_{0,jk} \quad \forall j \in \{1, 2, \dots, T-1\}, \forall k \in \mathbf{K} \quad (4)$$

$$P_{0k} + h_{0k} = X_{00k} \quad \forall k \in \mathbf{K} \quad (5)$$

$$X_{i0k} + Y_{i0k} = h_{ik} \quad \forall i \in \{1, 2, \dots, A_k\}, \forall k \in \mathbf{K} \quad (6)$$

$$X_{(i-1)(j-1)k} = X_{ijk} + Y_{ijk} \quad \forall i \in \{1, 2, \dots, A_k\}, \forall j \in \{1, 2, \dots, T\}, \forall k \in \mathbf{K} \quad (7)$$

$$X_{iTk} = 0 \quad \forall i \in \{0, 1, 2, \dots, A_k - 1\}, \forall k \in \mathbf{K} \quad (8)$$

$$X_{A_k jk} = 0 \quad \forall j \in \{0, 1, 2, \dots, T\}, \forall k \in \mathbf{K} \quad (9)$$

$$Y_{0jk} = 0 \quad \forall j \in \{0, 1, 2, \dots, T\}, \forall k \in \mathbf{K} \quad (10)$$

$$P_{jk}, X_{ijk}, Y_{ijk} \in \mathbf{I} = \{0, 1, 2, \dots\} \quad (11)$$

The objective function (Expression 1) minimizes the sum of purchasing, maintenance, operation, salvage, and emission costs over the period of analysis—that is, from time 0 (present) to the end of year T . Purchase costs cannot exceed the yearly budget (Expression 2). The number of vehicles in the fleet at any time must equal or exceed the minimum needed to cover the demand in terms of annual miles traveled (Expression 3). The number of vehicles purchased must equal the number of new vehicles for each vehicle type and year, except for the current time (Expression 4). The number of new vehicles used during year 0 must equal the sum of existing new vehicles plus purchased vehicles (Expression 5). Similarly, Expression 6 ensures the conservation of vehicles (i.e., initial vehicles—not age 0 vehicles—must be used or sold). The age of any vehicle in use will increase by 1 year after each time period (Expression 7). At the end of the last time period, there will be no vehicle in use for any age or type of vehicle (i.e., all vehicles will be sold at the corresponding salvage value, which is a function of vehicle type and age) (Expression 8). When a vehicle reaches its allowable maximum age, a function of vehicle type, it must be sold at the corresponding salvage value (Expression 9). A newly purchased vehicle should not be sold

before use (Expression 10). Finally, the decision variables associated with purchasing, utilization, and salvaging decisions must be integer-positive numbers (Expression 11).

SCENARIOS

Four factors are analyzed: annual vehicle utilization, gasoline prices, EV tax credits, and GHG emissions costs (Table 1). The values shown were established on the basis of (a) average vehicle utilization in the United States for vehicles that are less than 10 years old (about 13,000 mi/year) and miles driven by the demographic group with higher mileage (35- to 54-year-old men with an average of about 19,000 mi/year) (18), (b) average value of gasoline prices in the United States during the second half of 2010 and the highest ever gasoline price recorded in summer 2008 (19), (c) current U.S. federal government tax credit for EVs, and (d) median European value for GHG in \$/ton in the second half of 2010 (20).

The combination of categories and values presented in Table 1 generate the 16 scenarios in Table 2. For example, Scenario 1 (S1) is the baseline case (S0) but with high vehicle utilization (19,000 instead of 13,000 mi). Scenario 9 (S9) is the baseline case (S0) but with the addition of a federal tax credit of \$7,500 for EVs and a gasoline price of \$4.10 per gallon. If GHG costs are applied (i.e., S3) then $\text{ec} = \$18.70$, and \$0.00 otherwise.

DATA SOURCES

The VRM model presented in the previous section allows for a complete accounting and optimization of purchasing, operations, maintenance, and emissions costs. The model is data intensive because it requires that the analyst prepare matrices with purchase cost, operations and maintenance, salvage values, and emissions costs as a function of vehicle type and age or time period (V_{jk} , om_{ik} , s_{ik} , and em_{ik} respectively). Here it is assumed that data sources, vehicle types, and results are applicable to the U.S. market (Table 3).

Purchase prices in the United States were obtained from *Kelley Blue Book* (21). Similarly, depreciation and salvage values as a function of age and utilization by vehicle type were also obtained from *Kelley's Blue Book*. Purchase price includes manufacturer's suggested retail price, registration, and delivery, assuming that the destination is Portland, Oregon. In the case of EVs, there is no market or historical information on depreciation and salvage values. It is assumed that EVs have the same depreciation rate that hybrid vehicles have. Fuel efficiency is assumed to be the average of highway and city miles per gallon values using U.S. Environmental Protection Agency procedures (22). In the case of the Nissan Leaf, consumption of 0.25 kilowatthour/mi is assumed (23).

TABLE 1 Extreme Values Used for VRM Scenarios

	Vehicle Utilization (mi)	Gasoline Prices (\$/gal)	EV Tax Credit (\$)	GHG Cost (\$/ton)
Base case (Scenario 0 or S0)	13,000	2.72	0	0
Extreme case (Scenario 15 or S15)	19,000	4.10	7,500	18.7

TABLE 2 Sixteen Scenarios: Categories and Values

Scenario	Combination	EV Tax Credit	GHG Costs	High Gasoline Prices	High Vehicle Utilization
Scenario 0	Baseline				
Scenario 1	Combination 1				✓
Scenario 2				✓	
Scenario 3			✓		
Scenario 4		✓			
Scenario 5	Combination 2			✓	✓
Scenario 6			✓		✓
Scenario 7		✓			✓
Scenario 8			✓	✓	
Scenario 9	Combination 3	✓		✓	
Scenario 10		✓	✓		
Scenario 11			✓	✓	✓
Scenario 12		✓		✓	✓
Scenario 13	Extreme case	✓	✓		✓
Scenario 14		✓	✓	✓	
Scenario 15		✓	✓	✓	✓

Maintenance and operating costs were obtained from historical cost fleet data provided by the Oregon Department of Transportation (DOT) Fleet Management Division. Oregon DOT's fleet of sedans includes conventional and hybrid vehicles. Oregon DOT's Fleet Management Division has been collaborating with Oregon universities and other studies have considered Oregon DOT's replacement policies and cost functions (24). The typical period of ownership at Oregon DOT is less than eight years on average up to a maximum of 14 years. Hence, the period of analysis is assumed to be 14 years. To study the penetration of hybrids and EVs into conventional fleets, the initial fleet of vehicles is assumed to be 28 vehicles and the initial composition of the fleet is assumed to be Fords and Toyotas (50% for Fiesta and Yaris, respectively). Purchasing budget constraints are set to \$100,000 per year, which allows the purchase of up to five vehicles per year (using an average purchase price across vehicle types) (Table 3). In terms of fleet size, this translates to a maximum of 20% fleet turnover.

In terms of emissions, the level of GHG emissions associated with conventional vehicle use is estimated as a function of fuel efficiency, fuel type, and carbon content (25). For emissions associated with EVs, the most favorable scenario is assumed (i.e., 0 tailpipe emissions and 100% renewable green energy sources). In reality, a precise estimate of electric energy sources (clean versus dirty) can vary greatly as a function of time of day and location of the charging station (26, 27). The cost of GHGs was estimated by using the current European cap-and-trade value, around \$18.70/ton, although this value fluctuates widely over time (20). The cost of electricity is assumed to be \$0.12/kilowatthour (an average for the United States), although it

can vary greatly by time of day, location, and energy source. Energy equivalence in terms of Btus for fossil fuels and electricity was estimated by using coefficients from the *Transportation Energy Data Book* (28).

With regard to the value of the coefficients ep_k and es_k (manufacturing and scrapping, respectively), research results have consistently indicated that the utilization-based emissions (em_{ijk} , u_{ijk}) dominate. For example, for a generic U.S. family sedan driven 120,000 mi, the utilization share is more than 84% of the life-cycle energy and 87% of the generated carbon dioxide (29); similar conclusions were reached and used by other researchers (12). Unfortunately, emissions costs associated with producing and scrapping vehicles are the most difficult parameter to estimate (29–31). In addition, battery technology is advancing rapidly and it is difficult to forecast future GHG costs associated with manufacturing, mining, and vehicle mass (32). Furthermore, GHG emissions are directly proportional to vehicle mass (33), and EVs can be lighter or smaller because they have simpler mechanics and fewer components. Hence, because of the lack of current EV manufacturing and scrapping GHG data, the high degree of uncertainty associated with the available estimates, and high vehicle utilization (mileage), this research assumes a value of $ep_k + es_k = 8.5$ GHG tons for conventional vehicles and $ep_k + es_k = 9.5$ GHG tons for HEVs and EVs.

Finally, as purchase and operating costs take place over time, this research assumed a discount rate equal to the average 20-year treasury yield (34). High discount rates tend to penalize EVs because of their higher upfront purchase costs. The average 20-year treasury yield for October 2010, which is equal to 3.5%, was adopted here. This is an unusually low rate in part because of the current recession and U.S. Federal Reserve policies. A 0% discount rate may be acceptable for GHG emissions analysis as the effects of carbon dioxide on global warming can be felt for decades or even centuries. However, this approach is not appropriate for a private company, and the goal of this research is to analyze the current economic feasibility of different engine technologies.

RESULTS AND DISCUSSION

For each scenario, it is possible to minimize total costs over the planning horizon (Expression 1); for each scenario, the optimal evolution of the fleet is indicated by the decision variables X_{ijk} (vehicles in use),

TABLE 3 Vehicles Analyzed

Model Brand	Engine Type	Purchase Price (\$)	Efficiency (mpg)
Ford Fiesta	Conventional	13,320	34.5
Toyota Yaris	Conventional	12,605	32.5
Honda Insight	Hybrid	19,800	41.5
Nissan Leaf	Electric	33,720	99 ^a
Average		19,861	

^ampg equivalent.

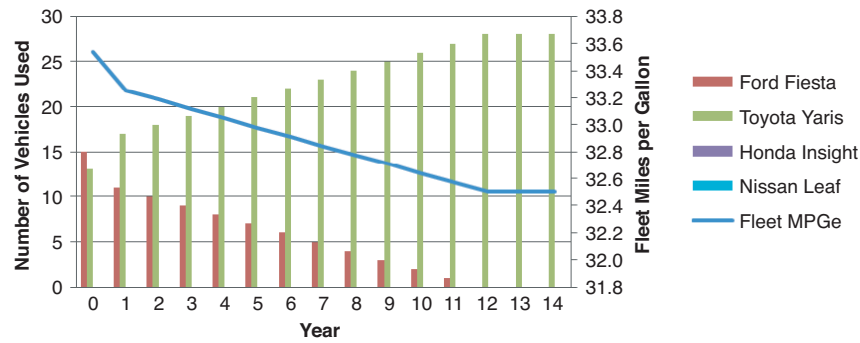


FIGURE 1 Baseline scenario vehicle decision progression.

Y_{ijk} (vehicles salvaged), and P_{jk} (purchases). For example, Figure 1 shows the number of vehicles in use over time for the baseline scenario (Scenario 0). In the base case, the number of Toyota Yaris increased steadily throughout the planning horizon because of their higher resale value (the Fiesta has the highest rate of depreciation). Conventional vehicles will dominate purchasing decisions in the near future if one assumes an average vehicle utilization rate, low fuel prices, no GHG costs, and no tax incentives for EVs. In this baseline scenario, the fuel efficiency of the fleet tends to decrease over time, because the model indicates that a consumer can save the most money by purchasing the Yaris. In the baseline scenario, the EV (Nissan Leaf) is not selected or purchased during the 14-year planning horizon.

Table 4 compares the baseline scenario (S0) with various single combination scenarios (S1 to S4) and highlights the percentage of changes in some key efficiency performance measures. For example, a 2.8% increase in Row 1–Column 1 indicates that higher vehicle use (19,000 mi/year per vehicle instead of 13,000 mi/year per vehicle) results in higher fleet fuel efficiency over the 14-year analysis horizon. This result is consistent with statistical analyses of the impact of fuel prices on automotive fleet composition, which have shown that higher fuel prices shift new auto purchases toward more fuel-efficient vehicles and accelerate the scrapping of older, less fuel-efficient used vehicles. Econometric estimates suggest that a 10% increase in gasoline prices from 2005 levels would generate a 0.22% increase in fleet fuel economy in the short run and a 2.04% increase in the long run (35).

The EV tax credit does not alter the optimal policy on its own (Table 4, S4–S0). However, high vehicle use leads to some of the most efficient outcomes on a per mile basis. Higher fuel costs or a carbon tax would also lead to a more efficient fleet and an overall reduction in energy consumption (in British thermal units per mile) and GHG emissions (in tons per mile).

Table 5 compares the baseline scenario (S0) with various double-combination scenarios (S5 to S10). Unlike the results shown in

Table 4, an EV tax credit combined with high fuel prices leads to a highly efficient outcome in terms of fleet efficiency, GHG emissions, and energy consumption (S9–S0). The combination of high gas prices and utilization also leads to efficient fleets (S5–S0).

Table 6 compares the baseline scenario (S0) with various triple-combination scenarios (S11 to S14). In this case, the combination of high fuel prices, high utilization, and tax credit (S12–S0) leads to the most efficient outcome in terms of fleet efficiency and emissions and energy consumption per mile; EVs are the most cost efficient in Scenario 12. As expected, the most efficient fleet and the lowest level of energy consumption and emissions per mile are obtained when all four factors are combined (Row S15–S0).

CONCLUSIONS

The VRM presented here integrates traditional fleet management costs with environmental elements, such as GHG equivalent life-cycle costs in terms of vehicle production and utilization. With real-world fleet and cost data, it was shown that VRMs can illuminate policy decisions and guide the use of public and private resources to reduce monetary and environmental costs. Sophisticated decision-making tools and models are needed to manage the complex trade-offs surrounding fleet management decisions.

For EVs to be competitive, tax incentives are needed in an economic context with relatively moderate fuel prices, higher initial purchase costs for EVs, and no carbon taxes. In economic terms, EVs are justified only with high gas prices and high utilization. Gasoline prices have great influence on vehicle replacement decisions and any increases will undoubtedly encourage the rate of purchases of vehicles with high mile-per-gallon rates. With increased utilization, the same trend will be observed; however, GHG emissions will not

TABLE 4 Individual Factors Versus Baseline

Scenario	Fleet mpg (%)	Final HEV and EV Fleet (% difference)	Total CO ₂ /mi (%)	Cost per Mile (\$/mi) (%)	Energy (Btu/mi) (%)
S1–S0	2.8	0.0	–6.6	–13.3	–2.7
S2–S0	2.8	0.0	–2.3	19.9	–2.7
S3–S0	1.6	0.0	–1.3	3.1	–1.5
S4–S0	0.0	0.0	0.0	0.0	0.0

TABLE 5 Two Combined Factors Versus Baseline

Scenario	Fleet mpg (%)	Final HEV and EV Fleet (% difference)	Total CO ₂ /mi (%)	Cost per Mile (\$/mi) (%)	Energy (Btu/mi) (%)
S5–S0	3.9	0.0	–7.5	6.4	–3.7
S6–S0	2.8	0.0	–6.6	–10.4	–2.7
S7–S0	2.8	0.0	–6.6	–13.3	–2.7
S8–S0	2.8	0.0	–2.3	23.0	–2.7
S9–S0	5.3	3.57	–5.0	19.9	–5.1
S10–S0	1.6	0.0	–1.3	3.1	–1.5

TABLE 6 Three and Four Combined Factors Versus Baseline

Scenario	Fleet mpg (%)	Final HEV and EV Fleet (% difference)	Total CO ₂ /mi (%)	Cost per Mile (\$/mi) (%)	Energy (Btu/mi) (%)
S11-S0	4.0	0.0	-7.6	9.3	-3.8
S12-S0	71.8	64.3	-47.3	2.4	-38.6
S13-S0	2.8	0.0	-6.6	-10.4	-2.7
S14-S0	10.5	10.7	-10.0	22.9	-9.5
S15-S0	72.8	64.3	-47.6	4.2	-38.9

be significantly reduced. The current price of carbon from European cap-and-trade markets does not affect replacement decisions as much as gasoline prices. The results clearly indicate that more research is needed to follow the evolution of market prices and technologies. Fluctuations in terms of batteries, fuel prices or carbon taxes, and tax incentives or government subsidies can lead to dramatic changes in competitiveness.

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REFERENCES

- Vyas, A. D., D. J. Santini, and L. R. Johnson. Potential of Plug-In Hybrid Vehicles to Reduce Petroleum Use: Issues Involved in Developing Reliable Estimates. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2139, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 55–63.
- HybridCars. <http://www.hybridcars.com/carmakers.html>. Accessed Oct. 10, 2010.
- Electric Cars: A Sparky New Motor. *The Economist*. <http://www.economist.com>. Accessed Oct. 9, 2010.
- Kelley Blue Book. *Kelley Blue Book New and Used Car Prices*. www.kbb.com. Accessed July 15, 2010.
- Bellman, R. Equipment Replacement Policy. *Journal of the Society for Industrial and Applied Mathematics*, Vol. 3, No. 3, 1955, pp. 133–136.
- Jones, P. C., J. L. Zydiak, and W. J. Hopp. Parallel Machine Replacement. *Naval Research Logistics*, Vol. 38, No. 3, 1991, pp. 351–365.
- Karabakal, N., J. R. Lohmann, and J. C. Bean. Parallel Replacement Under Capital Rationing Constraints. *Management Science*, Vol. 40, No. 3, 1994, pp. 305–319.
- Bethuyn, G. Optimal Replacement Under Variable Intensity of Utilization and Technological Progress. *Engineering Economist*, Vol. 43, No. 2, 1998, pp. 85–105.
- Hartman, J. C. An Economic Replacement Model with Probabilistic Asset Utilization. *IIIE Transactions*, Vol. 33, No. 9, 2001, pp. 717–727.
- Hartman, J. C. Multiple Asset Replacement Analysis Under Variable Utilization and Stochastic Demand. *European Journal of Operational Research*, Vol. 159, No. 1, 2004, pp. 145–165.
- Deluchi, M., Q. Wang, and D. Sperling. Electric Vehicles: Performance, Life-Cycle Costs, Emissions, and Recharging Requirements. *Transportation Research Part A*, Vol. 23, No. 3, 1989, pp. 255–278.
- Lave, L. B., and H. L. MacLean. An Environmental-Economic Evaluation of Hybrid Electric Vehicles: Toyota's Prius vs. Its Conventional Internal Combustion Engine Corolla. *Transportation Research Part D*, Vol. 7, No. 2, 2002, pp. 155–162.
- Chen, C., and J. Lin. Making an Informed Vehicle Scrappage Decision. *Transport Reviews*, Vol. 26, No. 6, 2006, pp. 731–748.
- Jin, D., and H. L. Kite-Powell. Optimal Fleet Utilization and Replacement. *Transportation Research Part E*, Vol. 36, No. 1, 2000, pp. 3–20.
- Lin, J., C. Chen, and D. A. Niemeier. An Analysis of Long Term Emission Benefits of a Government Vehicle Fleet Replacement Plan in Northern Illinois. *Transportation*, Vol. 35, No. 2, 2008, pp. 219–235.
- Dill, J. Estimating Emissions Reductions from Accelerated Vehicle Retirement Programs. *Transportation Research Part D*, Vol. 9, 2004, pp. 87–106.
- Spitzley, D. V., D. E. Grande, G. A. Keoleian, and H. C. Kim. Life Cycle Optimization of Ownership Costs and Emissions Reduction in US Vehicle Retirement Decisions. *Transportation Research Part D*, Vol. 10, No. 2, 2005, pp. 161–175.
- Hu, P. S., and T. R. Reuscher. *Summary of Travel Trends: 2001 National Household Travel Survey*. FHWA, 2004. <http://nhts.ornl.gov/2001/pub/STT.pdf>.
- American Automobile Association. *AAA's Daily Fuel Gauge Report*. www.fuelgaugereport.com. Accessed July 15, 2010.
- Point Carbon. *CO₂ Emissions Market Information Site*. www.pointcarbon.com. Accessed June 27, 2010.
- Kelley Blue Book. *Kelley Blue Book Online*. www.kbb.com. Accessed Nov. 27, 2010.
- U.S. Department of Energy. *Energy Efficiency and Renewable Energy*. www.fueleconomy.gov. Accessed July 15, 2010.
- Aksen, J., K. S. Kurani, and A. Burke. Are Batteries Ready for Plug-in Hybrid Buyers? *Transport Policy*, Vol. 17, No. 3, 2010, pp. 173–182.
- Kriett, P. O., W. N. Mbugua, D. S. Kim, and J. D. Porter. Equipment Replacement at Departments of Transportation: Prioritization Measures, Software Tools, and Supplementary Data. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2150, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 10–17.
- U.S. Environmental Protection Agency. *Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel*. <http://www.epa.gov/oms/climate/420f05001.htm>. Accessed July 15, 2010.
- Samaras, C., and K. Meisterling. Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy. *Environmental Science & Technology*, Vol. 42, No. 9, 2008, pp. 3170–3176.
- Elgowainy, A., A. Burnham, M. Wang, J. Mohlborg, and A. Rousseau. Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles. *SAE International Journal of Fuels and Lubricants*, Vol. 2, No. 1, 2009, pp. 627–644.
- Davis, S. C., S. W. Diegel, and R. G. Boundy. *Transportation Energy Data Book: Edition 29*. Oak Ridge National Laboratory, Oak Ridge, Tenn., 2010.
- Sullivan, J. L., R. L. Williams, S. Yester, E. Cobas-Flores, S. T. Chubbs, S. G. Hentges, and S. D. Pomper. *Life Cycle Inventory of a Generic US Family Sedan: Overview of Results of USCARAMP Project*. SAE International, Warrendale, Pa., 1998.
- DeCicco, J. M., and M. Thomas. A Method for Green Rating of Automobiles. *Journal of Industrial Ecology*, Vol. 3, No. 1, 1999, pp. 55–75.
- Udo de Haes, H., O. Joliet, G. Finnveden, M. Goedkoop, M. Hauschild, E. Hertwich, P. Hofstetter, W. Klöpffer, W. Krewitt, E. Lindeijer, R. Mueller-Wenk, S. Olson, D. Pennington, J. Potting, and B. Steen. *Life Cycle Impact Assessment: Striving Towards Best Practice*. SETAC Press, Pensacola, Fla., 2002.
- Scrosati, B., and J. Garcke. Lithium Batteries: Status, Prospects and Future. *Journal of Power Sources*, Vol. 195, No. 9, 2010, pp. 2419–2430.
- MacLean, H. L., and L. B. Lave. Evaluating Automobile Fuel/Propulsion System Technologies. *Progress in Energy and Combustion Science*, Vol. 29, No. 1, 2003, pp. 1–69.
- U.S. Department of the Treasury. *Daily Treasury Yield Curve Rates*. <http://www.treas.gov/offices/domestic-finance/debt-management/interest-rate/yield.shtml>. Accessed Oct. 28, 2010.
- Li, S., C. Timmins, and R. H. Haefen. How Do Gasoline Prices Affect Fleet Fuel Economy? *American Economic Journal: Economic Policy*, Vol. 1, No. 2, 2009, pp. 113–137.

Any omissions or mistakes are the responsibility of the authors.

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