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Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles

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HIGHLIGHTS

- ▶ Review of plug in hybrid total cost of ownership modeling to date.
- ▶ Development and documentation of more comprehensive plug in hybrid total cost of ownership models.
- ▶ Discussion of sensitivity of payback period to modeling parameters and scope.
- ▶ Many plug in hybrid vehicles can be characterized by high net benefits, short payback period, and high consumer preference.

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ABSTRACT

Motor vehicles represent one of the widely owned assets in the US. A vehicle's ownership cost includes fixed expenses to purchase and own the vehicle and variable costs to use and operate the vehicle. Policymakers, analysts and consumers are interested in understanding the total ownership costs of various vehicle types and technologies so as to understand their relative consumer preference and valuation. Plug-in hybrid electric vehicles are an advanced technology vehicle that is presently in limited production, but whose relative cost of ownership is not well-defined. A few studies have attempted to calculate the costs and benefits of PHEVs but none consider the cost and benefits of PHEVs at a level of detail comparable to what has been performed for other vehicle technologies. In order to understand the costs and benefits of PHEVs purchase and use, this study constructs a comprehensive ownership cost model. The model is then used to analyze different PHEV designs within four vehicle classes. This study then performs a sensitivity analysis to understand the sensitivity of total ownership cost and payback period to model parameters and the modeled components of ownership costs. Results show that a more comprehensive PHEV ownership cost model has a lower net cost of ownership than studies to date, resulting in a shorter payback period and higher consumer preference.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are hybrid electric vehicles which can draw and store energy from the electric grid. The benefits of plug-in hybrid vehicles are derived from their capability to displace petroleum energy for transportation with multi-source electrical energy. PHEVs are generally characterized by lower life-cycle petroleum consumption, lower fueling costs, lower criteria emissions, and lower carbon dioxide emissions than conventional vehicles [1], but at a higher manufacturing cost than conventional vehicles. Many automobile manufacturers have announced plans to develop and sell PHEVs in the US including: GM Chevrolet Volt in 2010, Fisker Karma PHEV in 2011, Toyota Prius PHEV in 2012, Ford C-Max Energi PHEV in 2012, Ford Fusion Energi PHEV in 2012, Mitsubishi Outlander PHEV in 2013, BYD F3DM in 2013, Honda Accord PHEV in 2014, Cadillac ELR in 2014, BMW i8 in 2014, Mitsubishi Px-MiEV PHEV in 2014 and Volvo V70 PHEV in 2014 [2].[1,2,3]

Despite their recent market introductions, the market potential, consumer acceptability, and economic efficiency of PHEVs are not well understood. A variety of studies have attempted to assess the market potential of PHEVs through tabulation of the fuel economy benefits and incremental costs of PHEVs [3–9]. These studies

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have generally concluded that in order for the PHEVs to reach economic and marketplace viability, technology advancements must decrease the incremental cost of the vehicle over conventional vehicle costs, and regulation or macro-economic forces must increase the price of gasoline fuels to above roughly $5.00 gallon^{-1} [6,9–11]. This consensus view of PHEV economics must be tempered by an understanding that these studies incorporate a wide range of scopes, vehicle usage models, ownership cost categories, and consumer preference models. Their analyses result in a wide variety of numerical valuations of PHEV economic efficiency, and these studies' assumptions and scopes have not been compared or synthesized.

The goal of the research effort documented in this paper is to more systematically synthesize a PHEV total cost of ownership (TCO) and consumer acceptability model so as to test this consensus view. This paper presents such a TCO model and compares it to the primary literature for PHEV techno-economic modeling so as to understand the effects of these studies' scope, methods and assumptions. A more comprehensive TCO model is shown to require significant increase in scope over previous models in literature. The TCO model proposed for this study includes models of various vehicle types, various PHEV types, vehicle purchase cost, loan cost, tax cost, insurance cost, annual registration cost, fuel cost, maintenance cost and salvage value. We then present the sensitivity of TCO and payback period to vehicle characteristics, economic assumptions and model scope. Survey data regarding consumer preference for PHEVs is then enrolled to understand the relationship between costs, benefits and consumers' willingness to pay for PHEVs. Finally, conclusions present a more comprehensive summary of the value, cost and market potential of PHEVs in the near-term.

2. Review of PHEV techno-economic studies

Four studies form the primary and most cited sources of information on the techno-economics of PHEVs (AEO [10] (85 Google Scholar citations); EPRI [3], EPRI [4] and EPRI [12] (19, 72, and 42 Google Scholar citations); Lemoine et al. [6] (75 Google Scholar citations); Simpson [9] (91 Google Scholar citations)). Other studies performing PHEV analysis cite these primary studies [8,13]. Model parameters and assumptions for these primary studies and this study are listed in Table 1.

Evaluation and synthesis of the results of these previous studies is complicated by differences between the scopes, assumptions and modeled components of each study. In order to design a more relevant, refined and comprehensive model of PHEV TCO and consumer acceptability, this study proposes to update the scope, vehicle usage assumptions, ownership costs and consumer preference models as shown in Table 1. For most categories, this TCO model is of larger scope than that of previous studies. For example, electricity and gasoline costs are projected rather than constant, this study uses a standardized utility factor (UF) [14] rather than outdated or low fidelity assumptions, and this study uses consumer preference surveys rather than simple cost-benefit analysis to represent the economic viability of the vehicles. In each category of classification shown in Table 1, this study aims to be more comprehensive, higher fidelity, and more defensible than previous studies.

3. Comprehensive TCO modeling methods

To determine the costs and benefits to consumers of a PHEV's purchase and use, we must construct a modeling environment that can connect individual PHEV's costs and benefits components. This study proposes a more comprehensive TCO model that includes all components of ownership costs as modeled in the literature and includes various other relevant ownership costs for PHEVs.

The baseline model is composed of sub-models where each model can be modified and adjusted individually and is described in detail in the sections following the discussion of TCO model scope.

3.1. Study scope

For this study, vehicles of similar fuel economy, functionality size, interior volumes and costs are grouped into vehicle fleets and vehicles classes following EPA vehicle classification methodology.[4] The four vehicle classes considered in our base model are Compact Car and Mid-Sized Car in the passenger car fleet, and mid-sized SUV and large SUV in the light truck fleet.

PHEVs can be designed to have different battery capacities, so as to satisfy consumers travel patterns and needs. Because each design will impose different costs and benefits to consumers, thirteen HEVs were designed and analyzed for each class of vehicles. The set of vehicles studied here includes grid-independent HEV0 (conventional hybrid electric vehicles) and grid-dependent PHEVs (of the PHEVx-type) with 5–60 miles of electric range [1].

HEV and PHEV incremental costs are derived by summing the costs of the Battery, Pack Hardware, Pack Tray, Pack Thermal, Traction Electric Motor, Traction Power Electronics, Traction Power Electronics Thermal, Charger, Charger Cable, Engine, Gasoline Storage Tank, Exhaust, Glider and Assembly Costs, Accessory Battery, and Transmission. The retail price equivalents (RPEs) reported here are derived from the EPRI PHEV studies as the averages of the "Base" and "ANL" methods at production levels of 100,000 units per year, inflated to 2010 currency [3,4]. Battery costs for modern lithium-ion (Li Ion) batteries are derived from [15] under the production scenario of 100,000 packs per year. The costs for each Li Ion battery are inflated to 2010 and added to the incremental component cost to represent the incremental cost of PHEV produced in 2010. The incremental RPE for every vehicle in this study is presented in Table 2, and Appendix A.[5]

3.2. Vehicle Usage

The distance driven in the first year of ownership for passenger cars and light-trucks is modeled as 12,000 mi (19,312 km) and 15,000 mi (24,140 km) respectively [18]. To account for decline in vehicle usage, yearly annual distance traveled declines at an annual rate that varies between 2.1% and 4.7% as in [19].

The gasoline fuel economy for CVs and HEVs is calculated using a utility factor (UF) weighted gasoline-only fuel economy method which assumes that the vehicle is charged on a daily basis. This method places no fuel economy cost on electricity since the petroleum content of marginal electricity is negligible. The method uses the SAE J2841 utility factor for urban and highway driving [14]. The gasoline fuel economy and electrical economy ratings were adjusted using EPA's labeling discount (10% for City and 22% for highway) to model real-world relevant fuel economy [20].

The energy consumptions for fully (FCTs) and partially charge tests (PCTs) are derived from previous work [3,4]. Eqs. (1) and (2) represent the calculated annual electricity consumption (E_a) and annual petroleum consumption (G_a) for each class and type of PHEV. Where VMT_a is the annual vehicle miles traveled:

[4] U.S. Environmental Protection Agency, "vehicle size classes", available at http://www.fueleconomy.gov/feg/info.shtml#sizeclasses.

[5] These incremental costs are comparable to other recent studies of PHEVs. For example, ANL calculates the incremental costs of a mid-sized PHEV 20 series vehicle (this study considers parallel vehicles) as $4701 in 2015, and $7347 in 2010 [16,17].