

Optimizing and Diversifying the Electric Range of Plug-in Hybrid Electric Vehicles for U.S. Drivers

Zhenhong Lin
Oak Ridge National Laboratory

ABSTRACT

To provide useful information for automakers to design successful plug-in hybrid electric vehicle (PHEV) products and for energy and environmental analysts to understand the social impact of PHEVs, this paper addresses the question of how many of the U.S. consumers, if buying a PHEV, would prefer what electric ranges. The Market-oriented Optimal Range for PHEV (MOR-PHEV) model is developed to optimize the PHEV electric range for each of 36,664 sampled individuals representing U.S. new vehicle drivers. The optimization objective is the minimization of the sum of costs on battery, gasoline, electricity and refueling hassle. Assuming no battery subsidy, the empirical results suggest that: 1) the optimal PHEV electric range approximates two thirds of one's typical daily driving distance in the near term, defined as \$450/kWh battery delivered price and \$4/gallon gasoline price. 2) PHEVs are not ready to directly compete with HEVs at today's situation, defined by the \$600/kWh battery delivered price and the \$3-\$4/gallon gasoline price, but can do so in the near term. 3) PHEV 10s will be favored by the market over longer-range PHEVs in the near term, but longer-range PHEVs can dominate the PHEV market if gasoline prices reach as high as \$5-\$6 per gallon and/or battery delivered prices reach as low as \$150-\$300/kWh. 4) PHEVs can become much more attractive against HEVs in the near term if the electric range can be extended by only 10% with multiple charges per day, possible with improved charging infrastructure or adapted charging behavior. 5) the impact of a \$100/kWh decrease in battery delivered prices on the competitiveness of PHEVs against HEVs can be offset by about \$1.25/gallon decrease in gasoline prices, or about 7¢/kWh increase in electricity prices. This also means that the impact of a \$1/gallon decrease in gasoline prices can be offset by about 5¢/kWh decrease in electricity prices.

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INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs), designed to operate on both electricity and gasoline¹, technologically promise reduction in petroleum use and pollutant emissions from the transport sector, while avoiding the range anxiety problem associated with battery electric vehicles and the lack of public refueling infrastructure faced by hydrogen-powered fuel cell vehicles[1, 2]. PHEVs also face the challenge of lack of charging infrastructure, but can incrementally attract consumers who can at least access home charging.

From the energy perspective, the PHEV powertrain operates in either of two modes-the charge depleting (CD) mode, where the PHEV is mainly powered by battery electricity, and the charge sustaining (CS) mode, where mainly by gasoline. The electricity stored in the battery may

come from onboard energy conversion of gasoline or from the grid via plug-in charging. The battery capacity directly determines the amount of grid electricity that can be stored onboard, and therefore determines the maximum distance a fully-charged PHEV can operate in the CD mode, called the electric or CD range. PHEVs consume little or no gasoline and emit little or no tailpipe pollutants in the CD mode. When the CD range is exhausted, PHEVs can be, but do not have to be, recharged to be able to continue operating, as they can operate in the CS mode and then be driven efficiently, just like non-plug-in hybrid electric vehicles (HEV), to as far as gas stations can be found. PHEVs can be designed so that there is no gasoline use in the CD mode. This type of PHEVs are called the pure CD mode PHEVs, as opposed to the blended CD model PHEVs, where the internal combustion engine may operate occasionally during the CD mode and

¹The fuel for PHEVs is not limited to gasoline. It can be any type of vehicle fuel. Gasoline-based PHEVs are chosen to be discussed in this paper for reasons of convenience and data availability.

result in a small amount of gasoline use. As to be shown later, this paper assumes the CD gasoline use rate to decrease with larger battery capacity, reflecting the assumption that small-battery PHEVs tend to be with the blended mode and large-battery PHEVs tend to be with the pure CD mode.

The electric range as a key vehicle attribute can significantly affect the market acceptance and social impact of PHEVs [3, 4]. Longer electric ranges reduce energy cost by allowing more substitution of electricity for gasoline, but demand more upfront payment on battery capacity. Longer electric ranges require larger and heavier batteries. The added battery weight requires extra power to maintain the vehicle performance, resulting in more powerful and heavier engines. Both added weights cause higher per-mile consumption of electricity and energy [5]. This results in a diminishing return of energy cost savings on paying for the incremental battery capacity. With respect to social impact, longer electric ranges enable more distance to be driven on electricity and less on gasoline, and usually imply less oil dependency and emissions, because vehicles are more efficient when running on electricity, and electricity production generally emits less and is supported by more diverse energy sources.

Therefore, how consumers will choose the PHEV electric range is of interest not only to automakers who want to design PHEV products for market success, but also to energy and environmental analysts who want to understand the social costs and benefits of PHEVs. There are three approaches to understanding the range preferences of future consumers. Revealed preferences surveys are not viable at present due to insufficient market data, as PHEVs have just entered the market. Stated preferences surveys have been conducted and generated some important insights about early PHEV consumers [6, 7, 8]. The common problem of stated preferences information is that consumers often behave differently from what they say they would do. The particular problem in using stated preferences surveys to understand PHEVs preferences is that PHEVs are not yet a familiar product and therefore correspondents may not fully understand what a different electric range means to them.

The third approach, adopted by this study, is related to the concept of component optimization [9, 10, 11, 12]. For the context of this study, it translates into the optimization of the PHEV electric range or battery size. The underlying notion is that if adequately informed, determined to buy a PHEV, and given all range options, a consumer would choose the electric range that minimizes the sum of all range-related cost items.

The major task is to develop and implement a method to optimize the PHEV electric range for any given consumer characterized by driving patterns and charging availability. The optimization objective is the minimization of the sum of range-related costs, including costs on battery, gasoline, electricity and refueling hassle. The method reflects the linkages that a longer electric range increases upfront battery cost and electricity cost and reduces gasoline cost and refueling hassle, and therefore an optimal range exists. The charging time is not considered a cost item, because PHEV

drivers are not expected to, like when refueling a gasoline vehicle, wait and essentially do nothing during charging. The optimization method is then implemented into the Market-oriented Optimal Range of PHEVs (MOR-PHEV) in MS Excel with data of 36,664 new vehicle drivers from the 2009 National Household Travel Survey (NHTS). Empirical results include the tipping points (where PHEVs and HEVs are equally competitive), the distribution of optimal PHEV range among US drivers, the statistical relationship of the optimal electric range with the annual and typical daily driving distances, the sensitivity of favoring rates of different PHEV products with respect to battery delivered prices, gasoline prices and the charging infrastructure adequacy.

OPTIMIZATION FRAMEWORK

The range-related consumer cost, or range cost (RC, in USD) is defined as the sum of four components (Equation 1)-the upfront battery delivered price (RC_b , in USD) as part of the PHEV vehicle price, the gasoline cost (RC_g , in USD) and the electricity cost (RC_e , in USD) from operating the PHEV, and the refueling hassle cost (RC_f , in USD) that reflects the inconvenience and annoyance of having to visit gas stations, all of which are in net present value.

$$RC = RC_b + RC_e + RC_g + RC_f$$

Equation 1

The charging time is not considered as a cost component. When recharging their PHEVs, drivers are expected to utilize the hours of charging time (e.g. sleeping if overnight home charging or dining if public charging at a restaurant), rather than wait beside the charger. This is different from gasoline refueling, where the time is short and the safety protocol requires the driver to stay with the nozzle. Neither is the possibly perceived hassle of charging considered. Such a hassle is not well understood, but survey results show that early PHEV adopters appear to be comfortable with or even enjoy plugging in their vehicles [7]. Some other survey results show that PHEV drivers adapt to the charging routine very quickly. These evidences suggest that the perceived inconvenience of recharging (at least at home) may be much less than that of refueling. After all, home is friendlier than gasoline stations and plugging in at the end of a trip is probably less a hassle than interrupting a trip for fuel.

The battery delivered price is the only part of the total vehicle price being considered here as simplification. It is possible that a larger battery may affect the costs of other vehicle components (e.g. requiring a more powerful engine), but these relationships are not known to be significant and thus ignored for simplicity.

Another ignored cost component is the charger cost at home. This paper focuses on the population who are already determined to buy a PHEV and therefore assumed to have at least the access to the Level I charging (110V). It is perceivable that consumers are more likely to upgrade to the Level II charging (240V). Such an upgrade is a good

supplement, but not considered required even for PHEV40s. A fully depleted PHEV40 can be fully recharged after ten hours with the Level 1 charger. For most drivers, ten hours of charging time at night is considered typically available, and the 40-mile range is not very often used up. Since the targeted drivers are all assumed to have the Level I home charging, the charger cost is not affected by the choice of electric range and thus does not need to be factored into the equation.

All four components of the range cost (RC) (Equation 1) are expected to change with the electric range (r , in miles). Particularly, with an incremental increase of the electric range (r), an increase in battery delivered price (RC_b) and electricity cost (RC_e) and a decrease in gasoline cost (RC_g) and refueling hassle cost (RC_f) are expected, causing the total range cost (RC) to change possibly in either direction.

The battery delivered price (RC_b) can be expressed as a function of the electric range (r), the on-board electric rate in the CD mode (E , in kWh/mile), the hypothetical HEV range (R_{HEV} , in miles, the distance driven by a HEV as if in the CD mode until the battery completely depleted), the unit battery delivered price (C_b , in USD/kWh), and the fixed battery delivered price (C_0 , in USD), as in Equation 2. The electric rate (E) is assumed to change with the electric range (r) due to added vehicle weight.

$$RC_b = (r + R_{HEV}) \cdot E(r) \cdot C_b + C_0$$

Equation 2

Assume that the random daily VMT (x , in miles) follows a probability density function $f(x)$ and that the PHEV's effective electric range is (rd), where the range extension ratio (d) represents the impact of charging infrastructure and charging behavior [13]. A range extension ratio of 100% means that the daily distance driven in the CD mode can only be less or equal to the electric range (r). If home, workplace and public charging are easily available and fully utilized, the range extension ratio (d) is expected to be larger than 100%. For example, if a PHEV with a 10-mile CD range is driven for 10 miles to the workplace, fully recharged there, and then driven back home, its range extension ratio is 200%. If there is no charging outside home and the home charging activity is not conducted as often as needed, then the range extension ratio (d) can be below 100%, meaning a reduced utilization of the battery capacity and a useless portion of the battery being carried every day.

The PHEV is assumed to operate all in the CD mode during days when the daily VMT (x) is below the effective range (rd), and in a mix of CD and CS modes during the other days. Also assume a PHEV will operate in the CD mode until the CD range is exhausted. If the CD range is exhausted before recharging, the vehicle operates in the CS mode until the next recharge.

Thus, according to the PHEV energy use formula [14], the electricity cost (RC_e) can be expressed as a function (Equation 3) of the on-board electric rate (E), the electricity price (P_e , in USD/kWh), the charging loss ($0 < L_c < 1$), the

effective electric range (rd), and the discounting ratio of annual payment to present value (P_A). The lifetime per-unit electricity cost (C_e , in USD/kWh) occurs as if one kWh of electricity is consumed onboard each day during the vehicle lifetime. $M_p(rd)$ (in miles) represents the truncated mean of daily VMT in the CD mode and $P(rd)$ represents the cumulative probability of daily VMT being below the effective electric range (rd).

$$\begin{aligned} RC_e &= \left(\int_0^{rd} E(r) \cdot P_e \cdot x \cdot f(x) \cdot dx + \int_{rd}^{+\infty} E(r) \cdot P_e \cdot r \cdot d \cdot f(x) \cdot dx \right) \cdot 365 \cdot P_A \\ &= E(r) \cdot C_e \cdot (M_p(rd) + r \cdot d \cdot (1 - P(rd))) \\ C_e &= P_e \cdot 365 \cdot P_A / L_c \\ M_p(rd) &= \int_0^{rd} x \cdot f(x) \cdot dx \\ P(rd) &= \int_0^{rd} f(x) \cdot dx = 1 - \int_{rd}^{+\infty} f(x) \cdot dx \end{aligned}$$

Equation 3

Also based on the PHEV energy use formula [14], the gasoline cost (RC_g) can be expressed as a function (Equation 4) of the on-board gasoline consumption rates in the CD mode (G_{cd} , gallon/mile) and the CS mode (G_{cs} , gallon /mile), the gasoline price (P_g , in USD/gallon), the effective electric range (rd), and the discounting ratio of annual payment to present value (P_A). Both gasoline consumption rates vary with the electric range. The lifetime per-unit gasoline cost (C_g , in USD/kWh) occurs as if one gallon of gasoline is consumed each day during the vehicle lifetime. M_x (in miles) represents the average daily VMT.

$$\begin{aligned} RC_g &= (G_{cd}(r) \cdot M_p(rd) + G_{cs}(r) \cdot (M_x - M_p(rd)) + (G_{cd}(r) - G_{cs}(r)) \cdot r \cdot d \cdot (1 - P(rd))) \cdot C_g \\ M_x &= \int_0^{+\infty} x \cdot f(x) \cdot dx \\ C_g &= P_g \cdot 365 \cdot P_A \end{aligned}$$

Equation 4

The refueling hassle cost (RC_f) has a similar function structure as the gasoline cost (RC_g), as in Equation 5, where C_{trip} (USD per refueling trip) represents the monetary value of refueling hassle cost and Q_{fillup} (gallon refilled per refueling trip) is the amount of gasoline refilled each time. So C_f (USD/gallon) is the equivalent gasoline tax per gallon that the consumer is willing to pay to avoid visiting the gas stations (but still paying for gasoline).

$$RC_f = (G_{cd}(r) \cdot M_p(rd) + G_{cs}(r) \cdot (M_x - M_p(rd)) + (G_{cd}(r) - G_{cs}(r)) \cdot r \cdot d \cdot (1 - P(rd))) \cdot C_f$$

$$C_f = \frac{C_{trip}}{Q_{fillup}} \cdot 365 \cdot P_A$$

Equation 5

The optimal PHEV electric range (r_0 , in miles) is one that minimizes the range cost (RC), i.e. $RC(r_0) \leq RC(r)$ for any electric range (r). This requires a zero first-order derivative and a positive second-order derivative of RC with respect to r (Equation 6). The prime symbol (') and double prime symbol (") respectively represents the first- and second-order derivative of a function with respect to the electric range (r). These two requirements, however, are not sufficient conditions for the range optimality, so extra steps are needed to compare possibly multiple local optimums as well as the boundary objective values. It should also be noted that the mathematical derivation so far is not dependent on the specific form of the probability density function $f(r)$.

$$\frac{\partial RC}{\partial r} = [E + (r + R_{HEV}) \cdot E'] \cdot C_b + [G'_{cs} \cdot M_x + (G'_{cd} - G'_{cs})M_p + (G_{cd} + G'_{cd} \cdot r - G_{cs} - G'_{cs} \cdot r) \cdot d \cdot (1 - P)] \cdot (C_g + C_f) + [E \cdot d \cdot (1 - P) + E' \cdot (M_p + r \cdot d \cdot (1 - P))] \cdot C_e = 0$$

$$\frac{\partial^2 RC}{\partial r^2} = [2E' + (r + R_{HEV}) \cdot E''] \cdot C_b + [G''_{cs} \cdot M_x + (G''_{cd} - G''_{cs})M_p + (G_{cs} - G_{cd})d \cdot P + (2(G'_{cd} - G'_{cs}) + (G'_{cd} - G'_{cs})r)d \cdot (1 - P)](C_g + C_f) + [2E' \cdot d(1 - P) - E \cdot d \cdot P + E''(M_p + r \cdot d(1 - P))]C_e > 0$$

Equation 6

QUALITATIVE DISCUSSION

For convenient interpretation, we can simplify Equation 6 into Equation 7 by assuming that 1) the energy consumption rates (E , G_{cd} , and G_{cs}) are constants (i.e. not a function of the electric range (r)) and 2) there is no underutilization or extended utilization of the battery capacity (i.e. $d=1$) caused by charging infrastructure and behavior.

$$\frac{\partial RC}{\partial r} = E \cdot C_b - [(G_{cs} - G_{cd}) \cdot (C_g + C_f) - E \cdot C_e] \cdot (1 - P) = 0$$

$$E \cdot C_b - B \cdot (1 - P) = 0$$

$$P(r) = \int_0^r f(x) \cdot dx = 1 - \frac{E \cdot C_b}{B} \quad 0 \leq P(r) \leq 1$$

$$B = (G_{cs} - G_{cd}) \cdot (C_g + C_f) - E \cdot C_e$$

$$\frac{\partial^2 RC}{\partial r^2} = B \cdot P > 0$$

Equation 7

By definition, the term $E \cdot C_b$ represents the marginal capital cost with respect to an incremental electric range,

while the term B represents the marginal operating benefit. Both terms are in comparable net present value. When the electric range (r) is sufficiently large to cover all daily VMT, it holds that $P=1$ and $(\partial RC/\partial r) = E \cdot C_b > 0$. This is logical, since at that point, all distances are driven in the CD mode and any extra battery capacity only serves to add upfront cost (but not weights or energy cost, since E , G_{cd} , and G_{cs} are assumed constant here).

The smaller $E \cdot C_b$ is or the larger B is, the larger the optimal range (r_0) is that satisfies $(\partial RC/\partial r) = 0$. Therefore, Equation 7 leads to the following arguments.

- A PHEV is preferred over a HEV ($r_0 > 0$) if and only if the marginal operating benefit (B) is positive and larger than the marginal capital cost ($E \cdot C_b$). The marginal capital cost ($E \cdot C_b$) is always positive, but the marginal operating benefit (B) can be negative if either gasoline prices are too low or electricity prices are too high. If $B < 0$ or $B < E \cdot C_b$, then the derivative of range cost ($\partial RC/\partial r$) is always positive, meaning that any incremental electric range always leads to higher range cost and therefore the optimal choice is zero electric range (i.e. HEV). This leads to an interesting question-what is the tipping point for a consumer to favor PHEVs over HEVs? This question will be addressed later in the section of Empirical Results.
- There is no need to increase the electric range that is already long enough to cover all daily VMT. When the electric range (r) is larger than all daily VMT (x), then $P=1$ and the derivative of range cost ($\partial RC/\partial r$) is always positive.
- Higher gasoline prices or lower electricity prices motivate the choice of longer electric ranges. This is captured by a higher marginal operating benefit (B), and therefore a larger P , and therefore a larger r .
- Longer electric ranges would be preferred if the per-mile electric rate (E) is decreased, which can be accomplished by lowering the vehicle weight or improving the efficiency of the CD mode.
- Consumers who are more adverse to visiting gas stations would choose longer electric ranges, because the term C_f is higher and the marginal operating benefit (B) is higher.
- Longer electric ranges would be preferred if the battery cost (C_b) is decreased.

THE MOR-PHEV MODEL AND BASELINE SETTING

The method established by Equation 1, 2, 3, 4, 5, Equation 6 is implemented into the Market-oriented Optimal Range for Plug-in Hybrid Electric Vehicles (MOR-PHEV) model (Figure 1), which optimizes the PHEV electric range for individual U.S. drivers based on credible data sources, including the 2009 National Household Travel Survey (NHTS)[15], the Autonomie model from Argonne National

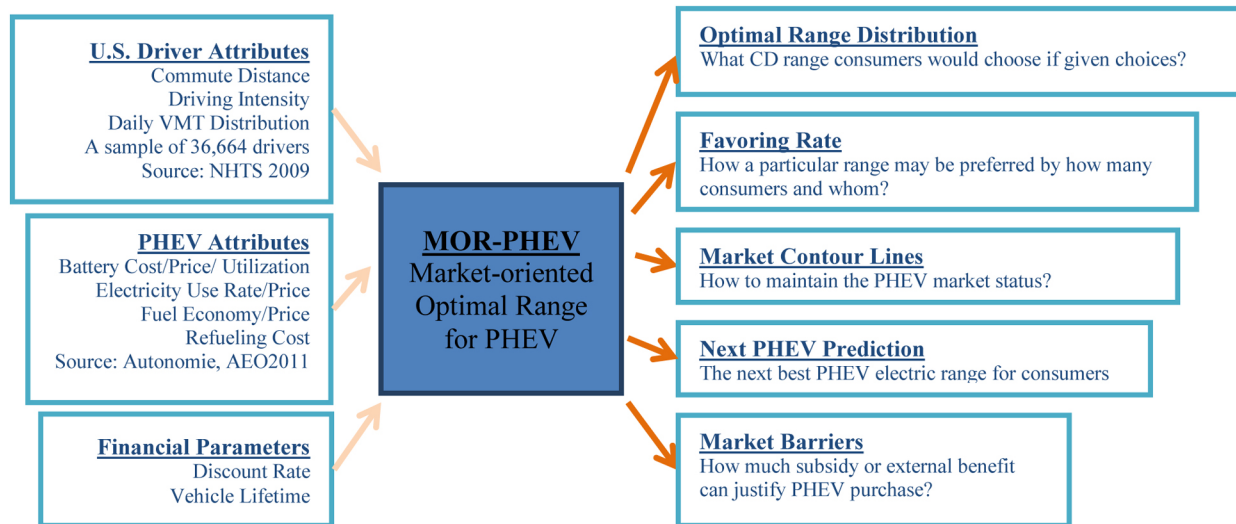


Figure 1. Illustration of the MOR-PHEV model

Laboratory[16], and the Energy Information Administration's 2011 Annual Energy Outlook [17]. The MOR-PHEV model takes into account relevant attributes of drivers and vehicles and generates information that is potentially useful for understanding the demand for and the social benefits of PHEVs. This includes: 1) Optimal Range Distribution among U.S. drivers, which shows how US drivers would choose the range if given full choices; 2) Favoring Rate by U.S. drivers on a particular PHEV range, which address how and why one PHEV range may be more likely to succeed than another or both succeed in different market segments; 3) Next PHEV Prediction, which shows the electric range of the next PHEV product that is most likely to succeed; 4) Tipping Points, where the market and technology conditions justify the preference of PHEVs over HEVs; and 5) Market Barriers, which are useful for analyzing the subsidy or external benefit as required to justify purchase of PHEVs against HEVs.

The next sub-sections explain the data and assumptions that form the baseline of MOR-PHEV. Some of these assumptions, such as battery unit cost and energy prices, can be changed if needed

DRIVER ATTRIBUTES

To generate a sample that represent drivers of new personal vehicles in the United States, the following filtering criteria are applied to the vehicle file of 2009 NHTS data.

- Main drivers can be identified.
- Age of the vehicle is less than or equal to 5 years.
- The vehicle is a car, a van, a SUV or a pickup truck.
- The vehicle does not have a commercial plate.

Several studies [13, 18] assume the Gamma distribution to characterize the random daily VMT, so does this study. This Gamma assumption has been validated with the GPS travel data of 382 vehicles [19]. Two pieces of information are

needed to specific each driver's unique Gamma distribution—the mean and the mode of daily vehicle miles travelled (VMT). The mean of daily VMT is obtained from annual VMT, which is collected in NHTS 2009. The mode of daily VMT is not so obvious, but can be reasonably estimated based on the commute distance, given that the driver is a worker with a fixed workplace location, rarely works at home, and go to work mainly by driving [14]. Therefore, the following filtering criteria are also applied for the purpose of estimating the individual daily VMT distribution.

- The main driver is a worker.
- Commute distance is available.
- The main mode to the workplace is driving.
- The main driver works at most 5 days at home per month.

The above filtering criteria results in 40,582 records of vehicle and associated driver data. About 9.7% of these records have at least one of the following driver attributes located outside of the 2 standard deviations from the sample mean: 1) the BESTMILE data field, which is the annual VMT of the vehicle estimated by Oak Ridge National Laboratory for NHTS 2009; 2) the great-circle distance from home to work; 3) the ratio of stated home-to-work distance to the home-to-work great-circle distance; and 4) the ratio of annual VMT to the commute distance. These outliers are removed, resulting in the final sample of 36,664 records being included in the MOR-PHEV model.

To calculate the optimal range based on Equation 6, the daily VMT probability density function $f(x)$ needs to be specified. About 66% of the sampled drivers have their daily VMT mode (M_d) less than the daily VMT mean (M_n), which suggests a positively skewed distribution and allows the shape (k) and scale (θ) parameters of the Gamma distribution to be estimated based on Equation 8 and Equation 9. The rest 34% drivers have a commuting-based mode larger than the