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On Modeling the Cost of Ownership of Plug-in Vehicles

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Summary

Plug-in vehicles (PEVs), which include battery-only electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), have steadily grown in sales amidst various incentive programs, but much speculation exists on when would PEVs become cost-competitive without incentives. This research adopts a bottom-up approach for estimation of purchase cost, and total cost of ownership (TCO). Baseline predictions, as well as sensitivity analysis (with more favorable conditions for PEVs) are generated for 2030. Results show few cases where TCO of PEVs could be less than a conventional internal combustion-engine (CICE) vehicle, but the purchase cost of CICE remains lower than all PEVs.

Keywords: PHEV (plug in hybrid electric vehicle), EV (electric vehicle), Purchase Cost, Total Cost of Ownership

1 Introduction

Plug-in vehicles (PEVs) refer to a subset of electric drive vehicles [1] that have sufficiently large traction battery and the capability to charge it via grid electricity, resulting in an appreciable fraction of the vehicle miles travelled (VMT) being powered by grid electricity. Though PEVs include battery-only electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and plug-in fuel-cell electric vehicles, this paper only focuses on PHEVs and BEVs. In addition to the higher efficiency of electric drive compared to conventional internal combustion-engine (CICE) vehicles, utilizing grid electricity for a large portion of VMT can (depending on grid generation mix) lead to a large reduction of greenhouse gas (GHG) emissions [2-6], which is a key desirable societal benefit.

Sales of PEVs have mostly seen steady growth in the US [7] in the presence of various incentive programs that include tax credits [8], purchase rebates [9], as well as other perks such as access to high-occupancy vehicle (HOV) highway lanes [10]. Much speculation exists on when/whether PEVs would/could be cost competitive in the mass market without any incentives. Two important metrics in assessing cost competitiveness include: i) purchase cost to a prospective owner, and ii) total cost of ownership (TCO), which also factors in a resale value and running costs throughout a period of ownership. While [11] shows that reducing GHG emissions via PEVs comes at an increased cost compared to CICEs, [12] predicts that BEVs could reach TCO parity, and even purchase cost parity with CICEs by the mid-2020s. In general, bottom-up approaches for cost estimation follow the same framework of: i) estimation of the cost of technologies/components to manufacture the vehicle, ii) estimation of mark-ups pertaining to vehicle acquisition, and iii) estimation of costs and/or credits throughout the vehicle ownership period. Depending on assumptions and/or cost forecasting models of various components, similar frameworks could lead to very different results. To help resolve some of those uncertainties in a transparent manner, the authors conducted an extensive review/critique of the literature and publicly available data sources [13], with the culmination of the work open-sourced into a publicly-accessible spread-sheet [14]. This paper provides a brief summary of the cost model and assumptions in [13], then extends the work and utilizes the spreadsheet to conduct sensitivity analysis with emphasis on various 2030 scenarios. Observations and inferred insights are then discussed and summarized.

2 Cost Modeling and Baseline Scenario

This section provides an overview summary of the cost model and the adopted inputs/assumptions. For a more detailed review and critique of the literature and data sources, interested readers may refer to [13]. The main categories of bottom-up cost model are:

i. Cost to build the vehicle. This includes cost estimates and forecasting for the vehicle powertrain, which (depending on vehicle powertrain type) includes several subsystems such as the engine, battery, motor, transmission and/or on-board charger. This category also includes direct cost for the rest of the vehicle (assumed to be approximately the same irrespective of the powertrain type), as well as indirect cost that accounts for various overheads (such as administration, equipment amortization/depreciation, research and development, …etc.)

ii. Mark-ups pertaining to vehicle acquisition. This includes OEM profit margin, dealer costs and profit margin, purchase tax, as well as costs for a home charger in case of first time PEV buyers.

iii. Cost and credits throughout the ownership period. Excluding various forms of incentives (since current analysis is focused on cost competitiveness without incentives), this includes running costs for fuel and/or electricity, registration and insurance, periodic maintenance, as well as a resale value at the end of ownership period. In case of BEVs, there could also be additional cost for a "replacement vehicle" (assumed to be a CICE) on days when the travel need exceeds the BEV range.

Some details of the cost elements are provided as follows:

- Direct cost of vehicle without powertrain was estimated at \$12,700 for non-BEV and \$12,600 for BEV per the tear-down report in [15], but this cost is increased (per the assumptions in [12]) by 6%, 5% and 21% for vehicle size categories in the US of Car, Crossover and SUV, respectively.
- Cost of battery system, which includes the cells, connectors, packaging, and thermal management, had some variation in estimated cost for 2018 in the literature surveyed in [13]. As such, a cost value for 2016 BEV batteries (\$273/kWh-pack), for-which there is better agreement in the literature, was projected to an estimated 2030 cost value from [16] (\$108/kWh-pack) at a fixed annual percentage reduction. Further details about battery system costs include:
    - PHEV batteries are 20% more expensive than BEV batteries in terms of \$/kWh at the pack level, per the assumption in [12].
    - Sizing of a battery pack to achieve a desired electric driving range depends on both the energy efficiency of a vehicle, as well as the battery swing (ratio of usable battery energy between charging/discharging limits to nominal capacity). Typical vehicle energy efficiency for 2018 and expectations for 2030 were adopted from [12]. On the other hand, battery swing is estimated to be 76% for PHEVs and 96% for BEVs, per typical vehicles in [17].
- Cost of motor system, which includes the motor, controller and power electronics, had much variation in the estimated cost for 2018 in the reviewed literature in [13]. An attempt at calibrating a regression model (from publicly-available retail prices data) in [13] led to the adoption of a first-order cost model of \$300 plus \$22.3/kW of motor power. Motor system is understood to be relatively mature technology and as such, the costs are assumed to be getting reduced by only 1% annually up to 2030, per [18].
- Cost of engine system, which includes the engine, air intake system, fuel system, controller, and exhaust system is also estimated via a first-order model (from [19]) of \$845 plus \$21.3/kW of engine power.

With engine technologies being mature, it is assumed that technology development efforts towards cost reduction are counter-balanced by the need to improve fuel economy, thereby resulting in no significant change in cost of engine system between 2018 and 2030.

- Cost of transmission system makes a distinction between the multi-speed or continuous-variable speed gearboxes used in CICEs and PHEVs, versus the single-speed reducers that are typically used in BEVs. With very limited publicly available data, a regression modelling approach in [13] resulted in cost estimates of $580 plus $14.6/kW for multi-speed or continuous-variable speed gearboxes, and $670 plus $3.8 for single-speed reducers. Similar to engine system, transmission systems are treated as a mature technology, with no significant cost changes expected between 2018 and 2030.
- Charging System includes the on-board charger and cables for PEVs, which are considered as part of the powertrain cost and are estimated at $423 per [15]. Charging system also includes acquisition and installation of a home charger for first-time PEV buyers. A home charger is not considered as part of the powertrain cost but is part of the total purchase cost. Per the data sources surveyed in [13], cost for a (Level-1) home charger for PHEVs is modelled at $300, while cost of a (Level-2) charger for BEVs is modelled at $1854. Similar to motor system, charging system costs are estimated to decline in cost by only 1% annually up to 2030.
- Indirect Cost in 2018 is estimated (per [15]) at 20.5% for mass-market CICEs and at 40% for BEVs since they include newer technologies and are produced in limited volume. In current work, PHEVs in 2018 are assumed to have the same indirect cost as BEVs, while all PEVs are expected to tend towards the same indirect cost of mass-market CICEs (i.e. 20.5%) by 2030.
- Other Mark-ups include OEM profit margin, which (per [12]) are assumed to be 5%, 10% and 15% for Car, Crossover and SUV respectively. In addition, the total purchase cost also considers 15% dealer mark-up (dealer operating costs and profit margin) and 8.5% purchase tax.
- Fuel/Electricity Costs depend on the vehicle efficiency in [gal/mile] and/or [kWh/mile], annual VMT, as well as the ratio of electric-VMT to total VMT, which is known as the utility factor (UF). In [13] and current work, real-world travel data from California household travel survey (CHTS) [20] is utilized for calculation of the UF for population average, as well as for sub-groups of vehicles that are “less urban” or “more urban” (per clustering analysis in [21]), as summarized in Table 1. For BEVs, the fraction of non-electric miles (on days when travel need exceeds the BEV range) are assumed to be done on a “replacement vehicle” that is a CICE of the same size class, and thus, BEVs may incur “gas cost”. The replacement vehicle is assumed to be a second household vehicle, and thus its usage cost (besides gas consumption) is assumed at a fairly low rate of $0.58/mile, $0.62/mile and $0.65/mile for Car, Crossover and SUV respectively. The cost of gas and electricity are obtained from statistics/predictions by US Energy Information Administration (EIA) [22, 23]. Average gas cost in 2018 was $2.81/gal and its baseline 2030 prediction is $3.36/gal, while average electricity cost was $0.128/kWh in 2018 and is predicted to be $0.130/kWh in 2030.
- Annual Registration and Insurance Costs are assumed to be the same for all powertrains (and are thus irrelevant in cost comparisons) but are included for completeness. The estimates are $285/year for registration [24], and $887/year for insurance [25].
- Maintenance Costs in [13] are based on a report from American Automobile Association (AAA) [26]. For CICEs, the costs are estimated at $0.085/mile, $0.091/mile and $0.096/mile for Car, Crossover and SUV respectively, while BEV Car maintenance costs are estimated at $0.066/mile. Due to lack of maintenance data for BEV Crossover and SUV, the cost for BEV Car is scaled proportionally using the ratios of CICE. PHEVs are assumed to have the same maintenance costs as CICEs.
- Re-sale Value after five years for a number of CICEs, PHEVs and BEVs at different zip codes was sampled in [13] using data from Kelly Blue book [27]. The average resale value was observed to be approx. 51% of the vehicle original value for CICEs and PHEVs. On the other hand, resale value for BEVs was approx. 40% of the vehicle original value.

Using those cost values, purchase cost and TCO in 2018, as well as a baseline scenario for 2030 is constructed and shown in Fig. 1. An extension beyond the work in [13] includes some distinction between serial and parallel

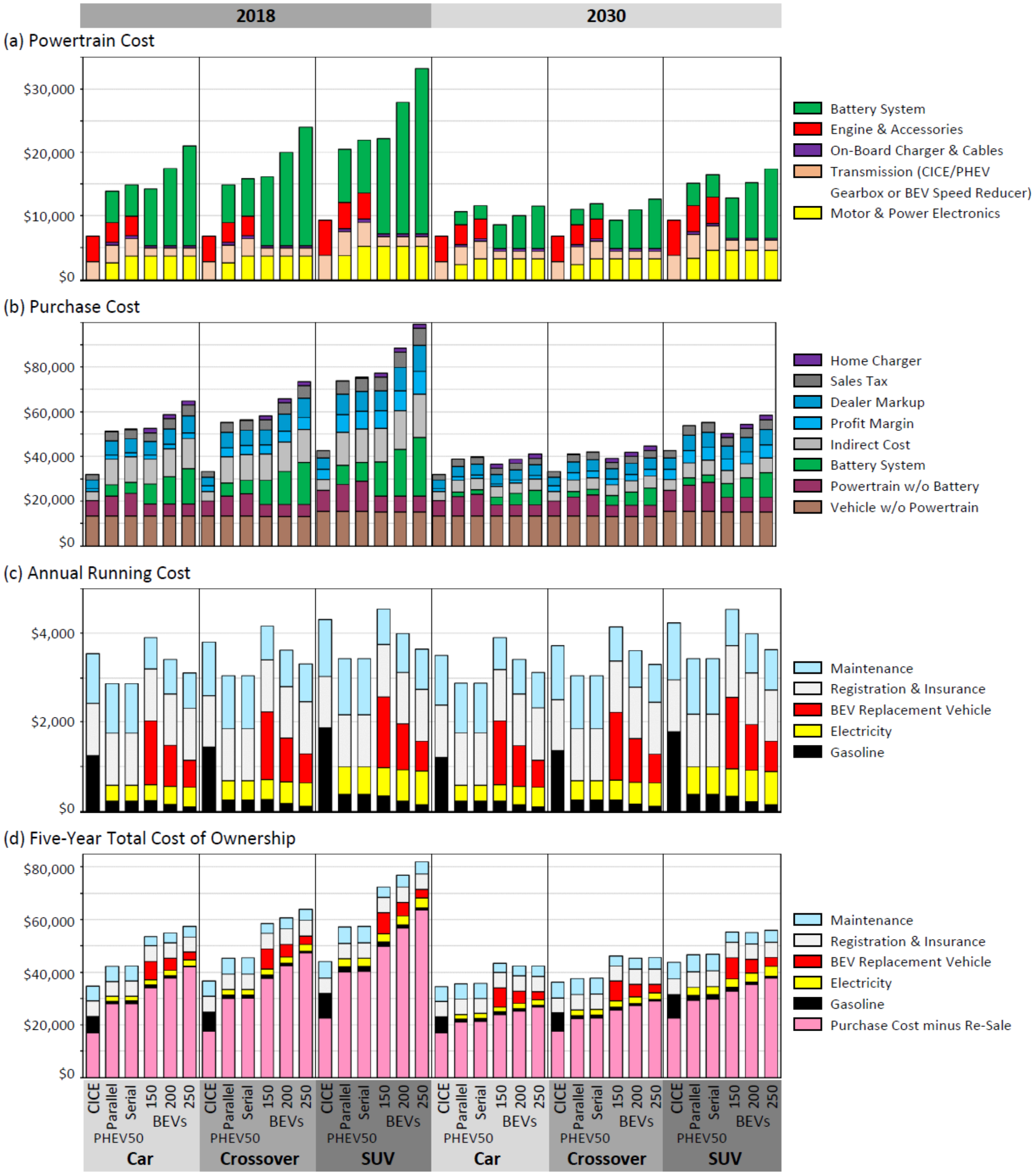


Figure 1: Baseline estimated costs of CICE and various plug-in vehicle models for 2018 and 2030

drive PHEVs. In [13] and the current study, the powertrain rated power (engine peak power for CICEs and motor peak power for BEVs) is 150kW for Car and Crossover, and 220kW for SUV, similar to [12]. In general, the engine of a PHEV is sized for average power demand (not peak power demand) and thus, PHEVs engine power is modelled at 70% of the rated powertrain power (per typical PHEV models on the market [17]). Distinction between serial and parallel drive PHEVs is primarily that a serial drive has no direct power flow path between engine and wheels, and thus its motor is sized similar to an equivalent BEV. On the other hand, a parallel-drive

PHEV can have both engine and motor simultaneously providing power to the wheels during instances of high-power demand. This allows for down-sizing of the required motor power while maintaining the same vehicle handling performance. In several real-world parallel drive PHEVs (as well as regular hybrids) [17], the motor power is less than the engine power. In current work however, we assume that the motor power matches the engine power (*i.e.* 70% of the powertrain rated power) for parallel-drive PHEVs. For that reason, the parallel-drive PHEV appears to have a small cost advantage (owing to reduction in motor cost) compared to serial-drive PHEV in Fig. 1. Further distinctions between serial and parallel drive PHEVs include: i) parallel drive allows better optimization of motor operating point (especially on highway travel), and thus improving overall efficiency of the vehicle and reducing running cost, and ii) transmission for serial drive PHEV can be as simple as that of BEV (in fact, some serial-drive PHEV models are referred to as an "electric vehicle with range extender"), thus allows reduction of the powertrain cost. However, accounting for the two latter distinctions between serial and parallel drive requires further data/detail than what is available in current model, and thus, is beyond the scope of this paper.

As a notation in current work, numeric annotation of a PEV model is an indicator of its electric range in miles. For example, PHEV50 implies a PHEV with 50 miles of electric range, while BEV200 implies a BEV with a range of 200 miles. Main observations from the baseline scenario shown in Fig. 1 include:

- Cost of PEV powertrains (Fig. 1.a) appears to be dominated by battery costs in 2018, with the lowest PEV powertrain cost (for parallel-drive PHEV50) being approx. $7,000, $8,000 and $11,200 more than CICE in the size categories of Car, Crossover and SUV respectively. Battery cost predictions in 2030 bring the difference in powertrain costs closer, with the lowest PEV powertrain cost (BEV150) at approx. $1,800, $2,500 and $3,500 more than CICE for Car, Crossover and SUV respectively.
- With cost of PEV powertrains being higher than that of CICE, and with all mark-ups being approx. the same, the purchase cost of all PEVs remains higher than CICE in 2030 for all size categories (Fig. 1.b). This includes the assumption that the indirect cost of all PEVs becomes the same as CICEs by 2030.
- Running cost of most PEVs (except BEV150) is lower than corresponding CICE (Fig. 1.c). While BEVs have lower maintenance cost compared to PHEVs, BEVs incur additional cost for a replacement vehicle for the non-electric fraction of VMT per their UF, resulting in PHEVs having overall lower running cost. Since UF, and by extent, the running cost, can vary significantly depending on vehicle usage pattern, in the upcoming sensitivity analysis section, VMT and UF values (Table 1) corresponding to less urban and more urban sub-groups of vehicle samples in CHTS dataset will also be considered.
- Another notable observation about running cost, is that the increase in unit price of gasoline and electricity for baseline 2030 scenario is mostly counter-balanced by improvements in vehicle efficiency across all powertrain types (per predicted vehicle efficiency values in [12]), resulting in no significant change in cost of gasoline and electricity between 2018 and 2030 for all powertrain types.
- Combining purchase cost and running cost over five years, then accounting for vehicle resale allows for estimation of TCO (Fig. 1.d). Though most PEVs have lower running cost than CICE, and despite the gap in purchase cost being relatively small for baseline 2030 scenario, savings in running cost over five years is insufficient to offset the difference in purchase cost in any of the studied vehicle size categories.

Table 1: Annual VMT and UF based on CHTS dataset

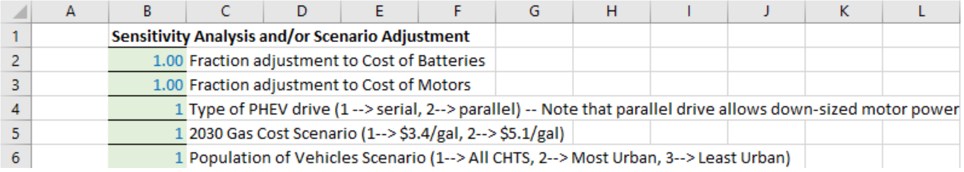
		CHTS Dataset Vehicle Samples		
		All CHTS	29% Least Urban	29% Most Urban
Average Annual VMT [mile/year]		13,250	18,144	6,944
Utility Factor [%]	PHEV50 - Parallel	72.6%	61.9%	93.9%
	PHEV50 - Serial	72.6%	61.9%	93.9%
	BEV150	81.4%	70.9%	99.1%
	BEV200	88.1%	81.3%	99.8%
	BEV250	92.2%	89.0%	100.0%

3 Sensitivity Analysis

The publicly open sourced spreadsheet [14] developed as a culmination of the cost modeling includes several tabs, with the summary tab including a section that allows for sensitivity analysis, as shown in Fig. 2. Aside from the previously discussed baseline scenario, the current work also considers (what is perceived to be) bounds for optimistic scenarios that are more favorable for PEVs. The optimistic scenarios include:

- Motor system (i.e. motor and power electronics) costs 20% less expensive than the 2030 baseline (which had assumed 1% annual cost reduction from 2018 to 2030), which is perceived to be an optimistic bound since motor systems technology is fairly mature. This adjustment is done by setting the value of the spreadsheet cell B3 (Fig. 2) to a value of 0.8
- Battery system costs 20% less expensive than the 2030 baseline (which had assumed \$108/kWh for BEV battery packs), implying \$86/kWh-pack, which is likely a bounding limit barring new battery technology getting discovered, since to the best of the authors' knowledge at the time of writing this manuscript, no OEM have made any official announcement regarding battery packs at less than \$100/kWh. This adjustment is done by setting the value of the spreadsheet cell B2 (Fig. 2) to a value of 0.8
- More expensive gasoline in 2030 by selecting the upper-bound prediction from [23], which is \$5.1/gal. This adjustment is done by setting the value of the spreadsheet cell B5 (Fig. 2) to a value of 2

In addition to adjustment of motor, battery and costs, the sensitivity analysis in this section considers different annual VMT and UF corresponding to different vehicle usage patterns. This is done by setting the value of the spreadsheet cell B6 (Fig. 2) to a value of {1, 2 or 3} for vehicle sub-populations corresponding to CHTS sample subsets (a shown in Table 1) of all CHTS, most urban and least urban, respectively.



	A	B	C
1		Sensitivity Analysis and/or Scenario Adjustment	
2		1.00	Fraction adjustment to Cost of Batteries
3		1.00	Fraction adjustment to Cost of Motors
4		1	Type of PHEV drive (1 --> serial, 2--> parallel) -- Note that parallel drive allows down-sized motor power
5		1	2030 Gas Cost Scenario (1--> \$3.4/gal, 2--> \$5.1/gal)
6		1	Population of Vehicles Scenario (1--> All CHTS, 2--> Most Urban, 3--> Least Urban)

Figure 2: Excerpt from the spreadsheet in [14] showing spreadsheet cells controlling sensitivity analysis

Since vehicle driving patterns and cost of gasoline affect the running cost (and by extent, TCO) but not purchase cost, the more optimistic purchase cost scenarios in current work consider: i) the less expensive motor system, ii) less expensive battery system, and iii) less expensive motor and battery systems, as shown in Fig. 3. As a note about Fig. 3, line plots are utilized for providing good visualization of the *contrast* between 2018 and 2030 (for example, difference in purchase cost from 2018 to 2030 for BEV250 Car is more difficult to eyeball in Fig. 1.b) but should *not be interpreted as interpolation* between 2018 and 2030 (since [14] only estimates cost values for 2018 and 2030). To aid in distinction between various scenarios, Fig 3 also includes zoom-in magnification (area surrounded by blue boxes in Fig .3) of the 2030 cost estimates. The main observation from Fig. 3 is that even in the most optimistic cost of technology scenarios (both Motor and Battery systems at 20% less than baseline), the least purchase cost PEV (which is BEV150 in 2030) is at approx. \$2,300, \$3,200 and \$3,800 more than CICE for the size categories of Car, Crossover and SUV, respectively.

Aside from baseline scenario, Fig. 4 shows TCO scenarios for different vehicle groups, with i) optimistic 2030 technology costs, and ii) optimistic 2030 technology costs along with more expensive gasoline. Main observations from Fig. 4 include:

- Due to efficiency improvements (per assumptions in [12]), there is no significant change in the TCO of CICEs between 2018 and 2030 in the baseline scenario (solid red lines in Fig. 4) despite the increase of gasoline price from \$2.81/gal to \$3.36/gal. In the more expensive gasoline scenario (\$5.1/gal) however (dashes with double-dot red lines in Fig. 4), there is a noticeable increase in the TCO of CICEs across all vehicle usage patterns for all size categories.

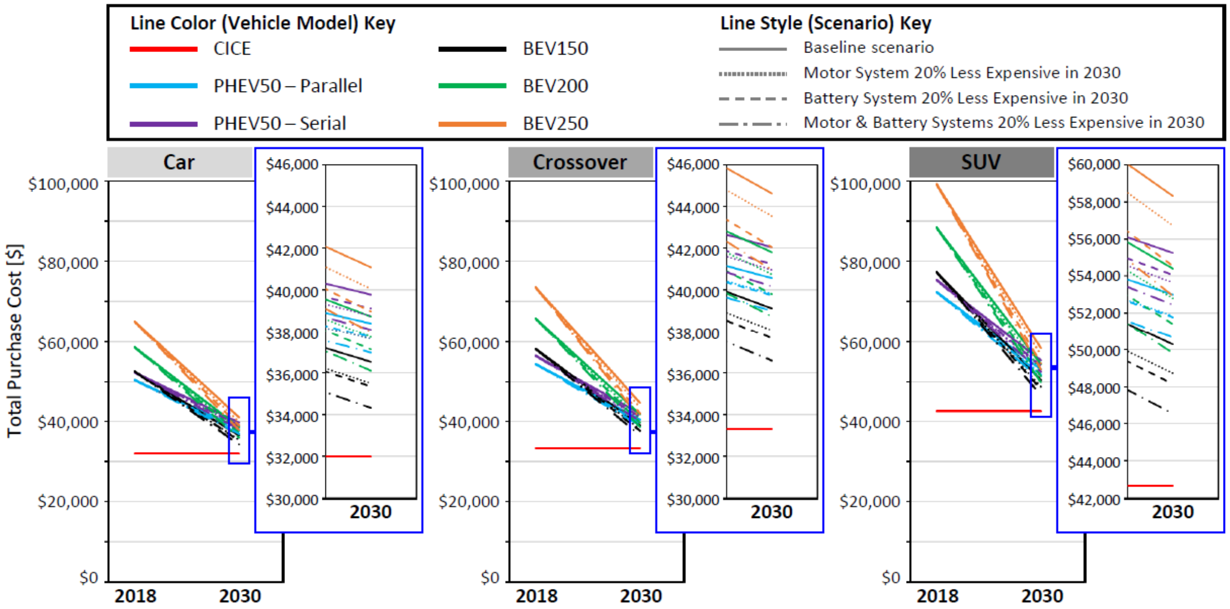


Figure 3: Purchase cost sensitivity analysis for various 2030 scenarios

- Per Table 1, all PEVs have some amount of equivalent gasoline usage (except BEVs in most-urban driving, which have zero or near-zero equivalent gasoline). As such, the line plots in Fig. 4 corresponding to optimistic technology costs (dash-dot lines) have lower cost values than the line plots for optimistic technology costs along with higher gasoline price (dash double-dot lines in Fig. 4), except for Fig. 4c, where the dash-dot and dash double-dot lines overlap for BEVs. Thus, when making observations via Fig. 4, comparisons should be among different line colours (powertrains) for same line style (scenario). Furthermore, there is no dash-dot red line in Fig. 4 since the more optimistic battery and more technology cost scenarios have no effect on the TCO of CICE.
- Driving patterns can have a large impact on the TCO of PEVs, and especially BEVs. BEV150 has the lowest 2030 TCO among BEVs for the most urban driving (Fig. 4.c), BEV200 has the lowest 2030 TCO among BEVs for population average (Fig. 4.a), while BEV250 has the lowest 2030 TCO among BEVs for the least urban driving (Fig. 4.b).
- Despite PEVs having high UF (less gasoline usage) for the most-urban vehicles group (Table 1), this sub-population of vehicles have low annual VMT (Table 1), resulting in the running cost savings not being enough to offset the difference in purchase cost minus resale value for any of the PEVs in Fig. 4.c when considering any same-scenario comparison (i.e. solid-line to solid line, dash-dot to solid red line or dash double-dot to dash-double dot) for any of the vehicle size categories.
- For the population-average driving pattern as represented by all CHTS vehicle samples (Fig. 4.a), the 2030 TCO of PHEVs can be lower than CICEs for all vehicle size categories when gasoline price is high. If gasoline price were to stay at the baseline 2030 prediction, it would take the more optimistic technology scenario for only the parallel-drive PHEV50 to barely break-even with CICE (comparing dash-dot blue line with solid red line in Fig. 4.a) in the Car and Crossover size categories, but not SUV.
- Despite lower UF (more gasoline usage) for the least-urban vehicles group (Table 1), high annual VMT (VMT) sets the 2030 TCO of PHEVs at a sizable margin below CICEs for the high gasoline price scenario (dash double-dot blue and purple lines compared to dash double-dot red line in Fig. 4.b) across all vehicle size categories. For this group of vehicles, PHEVs can reach break-even with CICE in terms of TCO even in the baseline scenario (solid blue and purple lines compared to solid red line in Fig. 4.b) for Car and Crossover size categories.

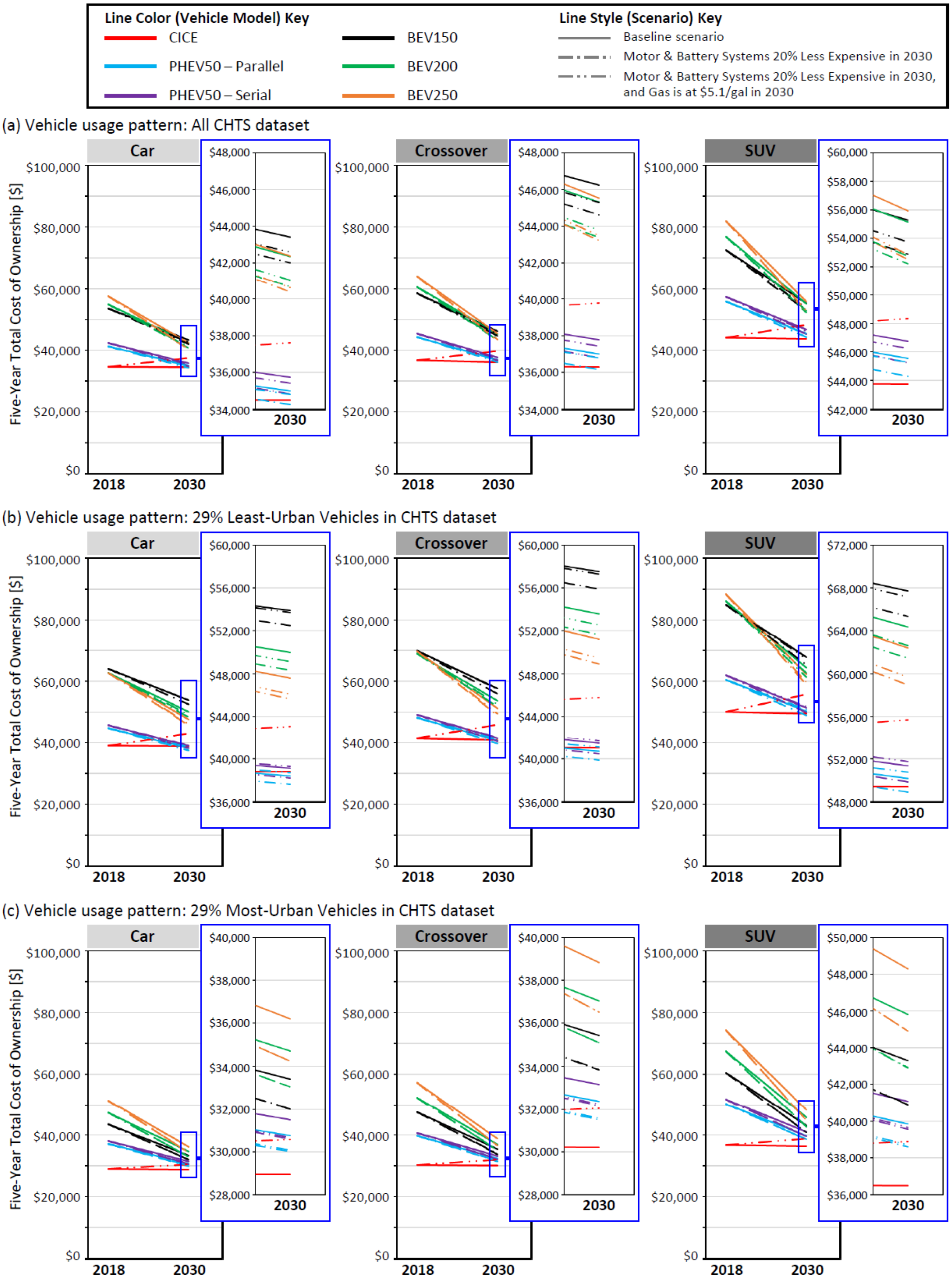


Figure 4: Total cost of ownership for different vehicle usage patterns, with sensitivity analysis for 2030 scenarios

Overall summary of the sensitivity analysis is that there exists some sub-populations of vehicle users and/or optimistic scenarios for-which the TCO of some PEVs can break even or become lower than the TCO CICEs by 2030 without incentives. However, without incentives, none of the modelled PEVs are expected to break-even with CICEs before 2030 in terms of purchase cost. It is important to note however that while purchase cost and/or TCO may be indicative of vehicle competitiveness, real human decision-making for vehicle choice (example of such work may be found in [28]) is a more complex process and is beyond the scope of current work.

4 Conclusion

A bottom-up cost modeling approach is adopted in this work, along with a review and critique of the literature and public data sources, for estimation of the purchase cost and TCO of three vehicle size categories of CICE, as well as several PEVs. The cost model is implemented into a publicly open-source spreadsheet and was utilized to generate a baseline scenario for 2018 and 2030, as well as sensitivity analysis for more optimistic/favorable assumptions for PEVs in 2030. Results of the sensitivity analysis shows parity in purchase cost without incentives is unlikely to happen before 2030. The 2030 TCO however may reach break-even without incentives between some PEVs and CICEs under some PEV favorable conditions (but not in the baseline scenario).

Future extensions of this work may include higher granularity in the sensitivity analysis by considering TCO at household-level (as opposed to partitioning the population into three groups), and/or considering different vehicle ownership models such as leasing and/or high VMT vehicles for mobility as a service (e.g. Uber & Lyft) applications.

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References

[1] US Department of Energy, http://energy.gov/sites/prod/files/2014/05/f15/52723.pdf, (2011) accessed on 2019-10-01

[2] J. Axsen, K. Kurani, R. McCarthy, C. Yang, *Plug-in hybrid vehicle GHG impacts in California: Integrating consumer-informed recharge profiles with an electricity-dispatch model*, Energy Policy, 39(2011), 1617-1629

[3] O. Karabasoglu, J. Michalek, *Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle power trains*, Energy Policy, 60(2013), 445-461

[4] T. Yuksel, M.A. Tamayao, C. Hendrickson, I. Azevedo, J. Michalek, *Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States*, Environmental Research Letters, 11(2016), 044007

[5] K. Laberteaux, K. Hamza, J. Willard, *Optimizing the electric range of plug-in vehicles via fuel economy simulations of real-world driving in California*, Transportation Research Part D, 73(2019), 15-33

[6] A. Jenn, I.L. Azevedo, J. Michalek, *Alternative-fuel-vehicle policy interactions increase U.S. greenhouse gas emissions*, Transportation Research Part A, 124(2019), 396-407

[7] Electric Drive Transportation Association, http://www.electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952, (2019) accessed on 2019-10-01

[8] US Department of Energy, https://www.fueleconomy.gov/feg/taxevb.shtml, (2016) accessed on 2016-01-01

[9] California Clean Vehicle Rebate Program, https://cleanvehiclerebate.org/eng, (2015) accessed on 2016-01-01

[10] California Environmental Protection Agency,

http://www.arb.ca.gov/msprog/zevprog/factsheets/clean_vehicle_incentives.pdf, (2012) accessed on 2016-01-01

[11] E. Traut, C. Hendrickson, E. Klampfl, Y. Liu, J. Michalek, *Optimal design and allocation of electrified vehicles and dedicated charging infrastructure for minimum lifecycle greenhouse gas emissions and cost*, Energy Policy, 51(2012), 524-534

[12] N. Lutsy, M. Nicholas, *Update on electric vehicle costs in the United States through 2030*, ICCT Working Paper, 2019

[13] K. Hamza, K. Laberteaux, K.C. Chu, *On Modeling the Total Cost of Ownership of Electric and Plug-in Hybrid Vehicles*, SAE World Congress, Detroit, MI (2020), 2020-01-1435

[14] Shared folder on Google Drive, https://drive.google.com/drive/folders/15aRR8WrrVV6ttqxSJXfcM8lNf0WrTgxK?usp=sharing, (2020) accessed on 2020-03-11

[15] UBS, *UBS Evidence Lab Electric Car Teardown – Disruption Ahead?* https://neo.ubs.com/shared/d1ZTxnvF2k/, (2017) accessed on 2019-10-01

[16] M. Anderman, *The xEV Industry Insider Report*. April 2019 Edition, https://www.totalbatteryconsulting.com/industry-reports/xEV-report/Extract-from-the-xEV-Industry-Report.pdf, (2019) accessed on 2019-11-01

[17] US Department of Energy, https://www.fueleconomy.gov/feg/printGuides.shtml, (2019) accessed on 2019-10-01

[18] National Research Council, *Transitions to Alternative Vehicles and Fuels. National Academic Press*, https://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels, (2013) accessed on 2019-10-01

[19] National Renewable Energy Laboratory, *Future Automotive Systems Technology Simulator*, http://www.nrel.gov/transportation/fastsim.html, (2018) accessed on 2019-10-01

[20] California Household Travel Survey, https://www.nrel.gov/transportation/secure-transportation-data/tsdc-california-travel-survey.html, (2013) accessed on 2019-10-01

[21] K. Hamza, K. Laberteaux, *A Cluster Analysis Study of Opportune Adoption of Electric Drive Vehicles for Better Greenhouse Gas Reduction*, ASME IDETC, Charlotte, NC (2016), DETC2016-59119

[22] U.S. Energy Information Administration, https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm, (2019) accessed on 2019-11-01

[23] Annual Energy Outlook 2019, https://www.eia.gov/outlooks/aeo/index.php, (2019) accessed on 2019-11-01

[24] US Department of Transportation, https://www.fhwa.dot.gov/ohim/hwytaxes/2001/pt11.htm, (2019) accessed on 2019-10-01

[25] US News, https://cars.usnews.com/cars-trucks/most-expensive-states-to-own-a-car, (2019) accessed on 2019-10-01

[26] American Automobile Association. Your Driving Costs, https://exchange.aaa.com/wp-content/uploads/2019/09/AAA-Your-Driving-Costs-2019.pdf, (2019) accessed on 2019-11-01

[27] Kelly Blue Book, https://www.kbb.com/, (2019) accessed on 2019-11-01

[28] J.P. Helveston, Y. Liu, E.M. Feit, E. Fuchs, E. Klampfl, J. Michalek, *Will subsidies drive electric vehicle adoption? Measuring consumer preferences in the U.S. and China*, Transportation Research Part A, 73(2015), 96-112

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