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Studying the spread – which future electric drive vehicles would do best under what circumstances?

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Summary

Two U.S.-based levelized-cost-of-driving (LCD) evaluations of light duty plug-in electric vehicles (PEVs) vs. conventional powertrains are expanded [1, 2]. For a single typical U.S. driving pattern, [2] implied that biofuels in internal combustion engines with limited plug-in electrification are best for enabling VKT from renewable energy sources. The input split PHEV50km and the range extended electric vehicle (REEV) in [1] were missing from [2]. These powertrains were added to [2] and an urban-only driving pattern evaluation added. Regarding introduction of renewable energy in light duty transportation, results imply that inclusion of significant plug-in electrified driving tapping into wind and solar renewable energy would enhance system cost effectiveness relative to relying alone on introduction of biofuels in advanced conventional powertrains with limited plug-in electrification.

Keywords: Plug-in Hybrid Electric Vehicle (PHEV), Extended Range Electric Vehicle (EREV), Range Extended Electric Vehicle (REEV, REX, BEVx), Battery electric vehicle (BEV), Levelized Cost of Driving

1 Studies Compared

Two recent U.S.-based levelized-cost-of-driving (LCD) evaluations of plug-in electric vehicles (PEVs) vs. conventional powertrains are expanded [1, 2]. Recent rapid changes in U.S. PEV model availability enabled and encouraged by previously unanticipated large reductions in costs of lithium-ion batteries [3] are considered.

The later of the two studies [2], projecting powertrain costs and configurations for 2025-30, examined two renewable liquid fuels (biofuels) options. Battery cost assumptions were aligned with the development of technologies that will reduce battery costs to a target of \$125/kWh by 2050 [2]. Batteries were assumed to last the life of the vehicle and to cost \$210-\$240/kWh in 2025 [2]. With one exception, powertrain evaluations were evaluated for the same annual kilometres driven when considering the LCD. The battery electric vehicle (BEV) with 145 km of on-road (not test certification) range was assumed to be unable to travel the usual annual U.S. distances, so it was assigned a lower total annual kilometres driven value. [2] implied that the least cost opportunity for vehicle kilometres of travel (VKT) via renewable energy in 2025-30 would be production of biofuels. Limited vehicle electrification via adoption of hybrid electric vehicles (HEVs) and plug-in hybrids with 16 km of range (PHEV16s) was estimated to be the lowest cost vehicle electrification option. BEVs with 145 and 338 km of range were estimated to have significantly higher LCD than PHEVs (16 & 56 km range) or HEVs.

[1] included comparisons of more types of electrified powertrain, but only one baseline gasoline powertrain. [1] examined three different types of annual driving, comparing urban-only driving to two different cases with varying amounts of intercity driving. For urban-only driving, a BEV with 150 km of range was estimated to have lowest LCD. For cases with intercity driving evaluated by U.S. experts, the lowest LCD case was a PHEV50 [1, 4]. Both German and U.S. experts evaluated separate cases, using different estimates of PEV costs. Each evaluated three different annual driving distances. At long annual distances, the Germans estimated overall electric drive cost-effectiveness of HEVs, PHEV30s and a range extended electric REEV70 using a series hybrid configuration for range extension, with minor difference in their LCD [1,5].

2 Plug-in Vehicle Technologies

2.1 Acronyms and/or terms used in [1] and/or [2]

2.1.1 Conventional drivetrains and liquid fuels for them

ICE = Internal combustion engine

SI = spark ignited (gasoline fuelled)

DI = direct injection (diesel fuelled) (biodiesel was evaluated in [2])

E85 = blend of predominantly ethanol and gasoline components (via corn stover in [2])

Pyrolysis = a thermo-chemical process of converting biomass to either gasoline or diesel fuels (in [2])

2.1.2 Electric drive options, arranged by usual degree of electrification

HEV = hybrid electric vehicle

IS = input split HEV powertrain. This powertrain uses two electric machines and is most efficient in urban driving. There is a mechanical link between the engine and wheels.

Parallel = HEV powertrain using only one electric machine. There is a mechanical link between the engine and wheels.

OS = output split HEV powertrain. Uses two electric machines. Compared to IS, greater efficiency improvement in highway driving. There is a mechanical link between the engine and wheels.

Series = One electric machine HEV powertrain with no link from engine to wheels. This powertrain is less expensive than IS and OS powertrains, but is much less efficient in highway driving.

PHEV = plug-in HEV. A broad term covering many options for combining (a) electric drive from grid electricity with (2) liquid-fuels-supplied drive from gasoline or diesel-like fuels. May use IS, OS, or series powertrains. In this paper we use a narrowed definition. A vehicle is a PHEV in the event that hard acceleration can cause the engine to come on to supplement the power from the battery.

REEV = range extended electric vehicle. As used here, any vehicle that has a liquid or gaseous fuel HEV capability but runs all-electrically while battery energy is not depleted, even if the driver presses very hard on the accelerator pedal

EREV = General Motors’ REEV which uses an OS HEV system when the battery pack is depleted.

REX = range extended electric vehicle – BMW REEV which uses a series HEV system when the battery pack is depleted.

BEVx = REX that meets California Air Resources Board regulatory requirements for all electric range of at least 120 km, limited gasoline range, and ultra low emissions.

BEV = battery electric vehicle. There is no ICE or liquid fuel assist. The vehicle runs only on electricity.

PEV = plug-in electric vehicle (PHEV, EREV, REEV, REX, BEVx and BEV)

FCEV = fuel cell electric vehicle. Uses an HEV powertrain with a battery along with a hydrogen fuelled fuel cell. The FCEV characterized in [2] does not plug-in.

2.2 Other important terms

LCD = levelized-cost-of-driving

ZEV = zero tailpipe emissions vehicle

CARB = California Air Resources Board. Regulatory authority that sets regulations and incentives for clean vehicles, including ZEV regulations and incentives.

ACC = advanced combined cycle. A highly efficient fossil fuel power generation technology usually using natural gas.

NG = natural gas. In [2] the estimated cost of ACC NG and wind electricity are equal. ACC NG is the lowest emitting major fossil fuelled power plant type.

CCS = carbon capture and storage. [2] evaluated this technology to remove carbon from ACC NG power plants and compared its costs to wind.

3 Baseline Results

Results from [2] that provide overlapping LCD cost estimates in [2013$/km] with an advanced conventional powertrain using pyrolysis gasoline are shown in Fig. 1. The ranges of costs shown in error bars are for vehicle powertrains, not fuels. [6] estimated that a higher octane gasoline, though more costly, would have net future benefits if engines and powertrains were designed to take advantage of its efficiency benefits. The possibility of producing high octane biofuel blendstocks other than ethanol is under investigation in the U.S. [7]. An emerging focus in [7] is on developing high octane blending components that can less expensively increase octane rating compared to ethanol. Accordingly, it is reasonable to consider a scenario where PEVs can be potentially competing with more expensive gasoline engines and fuels not available at present. It is also legitimate to think of “blending” of sources of electricity, focused on addition of other sources of renewable energy – wind and solar.

Fig. 1, presents [2]’s estimates for powertrains with LCD reasonably comparable with renewable gasoline. BEVs are missing in Figure 1. HEVs or PHEV16s are the only cost competitive powertrain electrification with renewable biofuel (gasoline) ICE. For such vehicles, the ability to introduce renewable wind and solar from the plug is very limited.

4 Leading Selling U.S. PEVs vs. 2025-30 Projections

We compared the PEVs characterized in [2] and its source simulations [8] to the vehicles in the market. [8] only simulates official fuel economy certification requirements for vehicles using standard urban and highway driving cycles. Authors of [2] wanted on-road fuel economy estimates, so the values predicted in [8] were discounted in [2] by use of a fuel economy adjustment formula developed by U.S. Environmental Protection Agency (EPA). [1] had instead run a range of both certification-test and on-road driving cycles. Simulations from [1] were used to predict on-road fuel/electricity consumption for the revised comparisons that we present here. The LA92 driving cycle was used for urban driving and the US06 Highway cycle was used for intercity highway travel. The estimates were compared to the EPA’s “window sticker” estimates of fuel consumption that are provided to U.S. consumers in fueleconomy.gov and on the vehicle’s window at the dealership. The electricity consumption of the simulated BEV145 in kWh/100 km (13.5 urban, 17.4 highway) can be compared to the kWh/100 km of the recently introduced Hyundai Ioniq BEV (14.1 urban, 17.3 highway). Although the Ioniq has a larger rated range of 200 km, which should push up its mass relative to the simulated BEV145, it has almost identical kWh/100 mile ratings. The kWh/100 km of the BEV338 (15.5 urban, 19.0 highway) may be compared to the new Chevrolet Bolt BEV383 (16.2 urban, 18.8 highway). Based on these comparisons, BEV electricity consumption estimates projected/simulated in [1] and [2] are available today, but in BEVs that are superior in range.

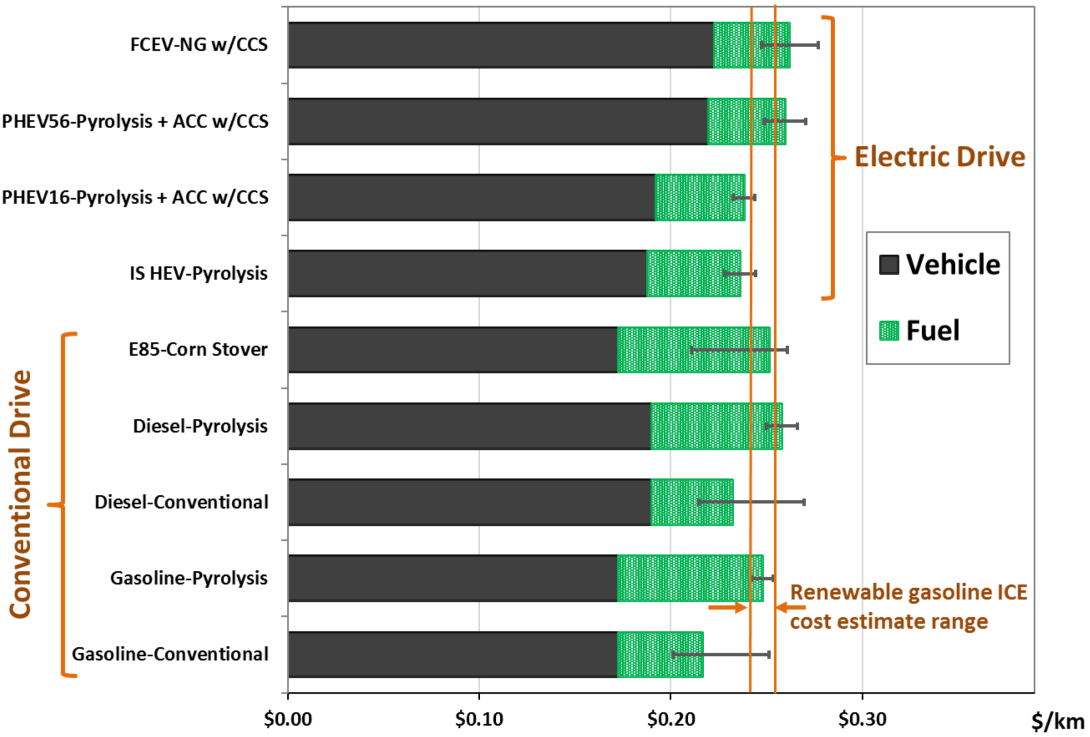

Fig. 1. Initial case levelized cost of driving for an analysis window of 5 years, 5% discount rate [2][1]

Another key attribute of PEVs is the range that they are able to attain. While [2] estimated the range of a mid-size BEV338, the leading selling U.S. midsize BEV, the 2017 Tesla Model S, has rated ranges from 338 to 544 km depending on model. The OS EREV simulated/characterized in [2] had a range of 56 km. The rated range of the present GM OS EREV is 85 km. Admittedly, that EREV does not have mid-size interior space. [2] characterized a future FCEV. There are currently few available models in limited quantities. [2] characterized an IS PHEV16. Honda and Toyota had previously produced such vehicles but have since discontinued them. Honda has announced that it will bring a mid-size PHEV66 to market in coming months. Toyota has replaced the Prius IS PHEV18 with an IS PHEV40, the midsize Prius Prime. Thus, the only PHEV that was estimated in [2] to be a cost effective plug-in, the IS PHEV16, has been discontinued by those manufacturers that previously produced such vehicles, which are being replaced with PHEVs with range from 40-66 km. The Toyota Prius IS HEV is the leading 2017 seller among HEVs. Its rated urban fuel consumption is 4.36 U.S. liters/100 km, while the highway rating is 4.70. For the 2025 HEV in our evaluations, the urban value is 4.00 and the highway value is 5.25 liters/100 km. Another mid-size HEV from Toyota, the Camry, has ratings of 5.60 and 6.19 liters/100 km, respectively. The best available mid-size HEV, the Hyundai Ioniq Blue is rated at 4.13 liters/100 km urban, 3.99 liters/100 km highway.

As previously noted, in [1] German expert estimates of the cost effectiveness of a series REEV were more favourable than U.S. expert estimates. The only REEV being sold in the U.S. is a German model, the BMW i3 REX. The CARB range requirement minimum to get a BEVx rating was met by this REEV. The U.S. window sticker rated range (on-road range) was 116 km; the requirements (under different test conditions) to satisfy CARB was 121 km. For this study we approximate a new REEV that would have an on-road all-electric range of 116 km, assuming that such a vehicle could be equipped with a 5 gallon gasoline tank and satisfy CARB requirements for the BEVx rating. However, we also assume that a larger fuel tank could be used in the rest of the U.S. (outside California), providing good intercity driving capability on gasoline or bio-gasoline blends. Our assumptions are based on the “U.S.” estimates.

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[1] 5-year analysis window represents initial purchaser perspective; 15-year analysis window represents all users perspective during a vehicle’s life – both initial purchaser and used vehicle purchasers.

5 Evolution of Retail Price Projections

As noted in [3] lithium-ion battery costs dropped precipitously ‘in the last two years”, as had been previously predicted would be possible [9, 10]. This was a surprise to many [3]. Authors of [2] were aware of these changes, which were reflected in their cost projections. As a result, there were some significant changes in estimates of retail prices attainable in the short span of 2 years between [1] and [2]. When we compared price estimate simulations for similar powertrains across studies [1] and [2], it was clear that estimates of costs of vehicle electrification in [2] captured the drop in battery cost (Fig. 2).

Clearly the pattern of these changes was relatively favourable to longer range PEVs. A comparison of the IS PHEV56 and the OS PHEV56 implies that battery, and perhaps electric machinery, cost reductions might also have been involved. Higher cost reduction of the OS PHEV56 vs. the IS PHEV56 is largely due to the higher power and cost of the battery [10] and electrical machinery [11] needed to assure all-electric operations under all driving conditions.

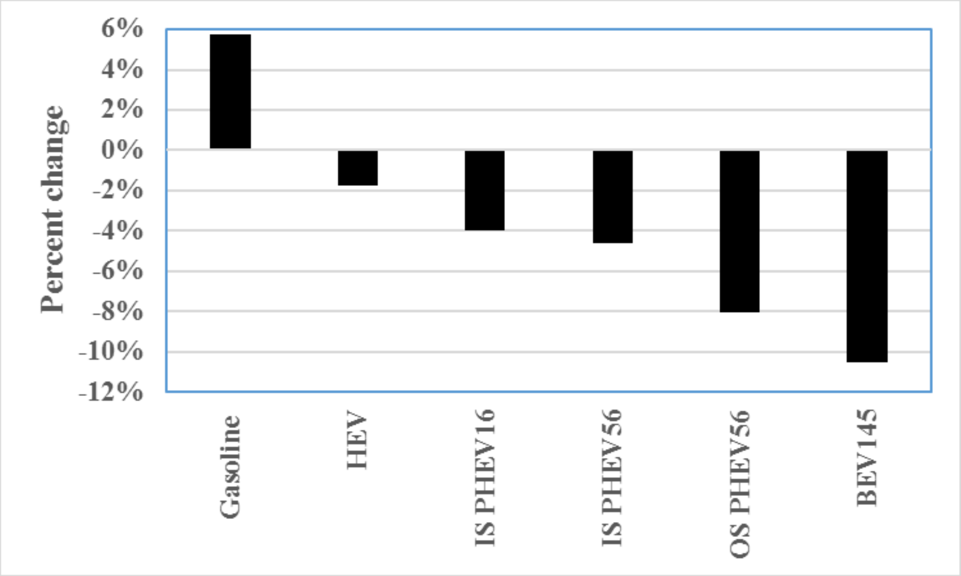

Fig. 2 Percent change in comparable model retail price, study [2] vs. [1]

6 Changes to Simulation Assumptions

Comparing the mix of PEVs simulated in [1] vs. [2] to the mix of available PEVs in the U.S. market, it was observed that [2] did not include two important cases in [1], which are in the present U.S. market. These were an “input-split” (IS) PHEV50 and a series range extended electric vehicle (REEV) comparable to the PHEV70 in [1] (i.e. REEV70 in this paper’s terminology). Simulations and cost estimates of the IS PHEV50 from [1] were used to construct a similar, updated IS PHEV56 case based on cost estimates from [2]. Similarly, a REEV116 approximation was constructed. The on-road 116 km range capability was selected because that range would allow a modified HEV capable version to be built that could qualify as a CARB BEVx.

6.1 Vehicle kilometres of travel

We define VKT to develop the LCD estimates for two cases: base and urban-only. For our base case, we use the same VKT assumptions as [2], which were based on NHTSA’s passenger car travel distance schedule over a 15-year lifetime [4]. In this case, each vehicle drives 22,903 km in year one, with VKT gradually decreasing to 14,885 km in year 15, and the 15-year VKT totals 286,627 km. For our simulations of the average U.S. driving, we assumed 25% of the kilometres driven were inter-city driving. [5] compared the annual miles of various BEVs in the U.S. The leading selling mass market BEV, the Nissan Leaf, averaged 16,560 km/yr, which was 76% of the annual miles of the long range Tesla Model S luxury BEVs. Thus, our use of 75% of kilometres for the “city BEV” (BEV145) urban-only case is consistent with the realized results for the leading early city BEV (117-135 km rated range) and long range luxury BEV (223-434 km of rated range for models available in the evaluation period). In our urban-only case, we assume the vehicles are not used for intercity travel and drive 25% less than the base case with the 15-year VKT equal to 214,970 km.

6.2 Vehicle price and charging infrastructure cost

We use the mid-case vehicle prices for each of the vehicle types characterized in [2]. For the two added PEVs, i.e. PHEV56 IS and REEV116, we developed cost estimates relative to a specific comparable vehicle in [1] to ensure consistency. For the IS PHEV56 IS, we examined study [1]'s price increment for its IS PHEV50 between its HEV and its OS PHEV50. We calculate the IS PHEV56 price increase over the HEV to be 40% of the difference between the HEV and OS PHEV56 (Table 1). For the REEV116, we add the price differential between the 2017 BMW i3 and BMW i3 REX ($3,850) [12] to estimate the range extender option's engine and HEV transmission price change. We also assume that a smaller battery for the REEV116 would cost $1,000 less than a BEV145. In terms of list price reduction per kilometre of electric range reduction, this is about 10% less than the 2017 price difference between the 183 km range BMW i3 BEV and the 130 km version [12].

For our two cases, we estimated both EVSE (electric vehicle supply equipment) and electricity prices based on a local utility incentivizing PEV adoption while using strategies to obtain the benefits of well-managed PEV charging [13]. In each scenario, the utility provides discounted EVSE and electricity prices to the consumers. In the base and urban-only cases, the utility inspects the consumer's garage to determine the suitability of existing circuits for PHEV and BEV use. For consumers choosing PHEVs, if a dedicated circuit [13] has to be installed, the utility and consumer will split the cost equally, $600 each, for the installation and a simple wall mounted L1 EVSE [14]. For consumers that do not require a dedicated circuit, the utility will not charge for the inspection if they use a L1 EVSE that comes with the vehicle. We assume that only half of the inspections require a new dedicated circuit, making the average cost for PHEV owners $300. The benefit to the utility is that the consumer utilizes the low power L1 charging (~ 1.0-1.4 kW), which favourably spreads overnight electric charging load over longer hours [13] and incentivizes consistent overnight charging every day of the week.

For consumers choosing BEVs, we assume that the residential location of the prospective owner has enough electrical system power for L2 EVSE charging of BEVs (~ 7kW) and is therefore a relatively good candidate for utility installed control of charging. In this niche market scenario, the utility pays the entire installation equipment cost of the dedicated circuit, controls, and L2 EVSE. The benefit to the utility is that the consumer utilizes "actively controlled" (i.e. utility can control charging time and power) L2 charging. The net EVSE costs to PEV purchasers cooperating with utilities are summarized in Table 1.

6.3 Share of kilometres driven electrically

[2] presents one set of estimates for average U.S. driving distance. The authors assumed that BEV145 vehicle has lower VKT than longer range vehicles. Given consistent total driving statistics for short range BEVs in [5], we agree with that assumption, but we exclude it from the vehicles considered in the base case, and substitute it with an estimate for a REEV116. This is in contrast to [2], where the BEV145 remained in the evaluation, but its costs were spread over less kilometres of service, thus increasing its average LCD relative to other vehicles with longer driving range. Fuel consumption estimates were developed by approximation, examining the REEV70 simulations for [1], the BEV145 estimates from [2], and the urban vs. highway ratings of the BMW i3 BEV vs. the i3 REX [12].

California Air Resources Board (CARB) recently compiled annual VKT and "eVKT" miles for BEVs and PHEVs [5]. Results regarding the share of eVKT for PHEVs are plotted in Fig. 3. These evaluations showed different eVKT shares than used in [2]. For the PHEV56 study, [2] assumed 58% eVKT. Based on the recent CARB results [5] we revised this to 70% (Table 2). Note that the 2011-13 Chevrolet Volt required premium gasoline (high octane gasoline), which is more expensive than regular gasoline grade. This is consistent with the expectation that future vehicles would be designed to use high octane gasoline [6] or bio-gasoline blends [7]. Thus, we assume that PHEVs and REEVs would use advanced high octane fuels when driving between cities or when extended urban driving took them beyond the electric range.

Table 1: Initial Consumer Cost Estimates

	Vehicle	**Electric Charging Equipment**
Powertrain Type	**[2] Mid-case**	**Base & urban** (see text)
SI ICE Gasoline	$23,491	N/A
DI ICE Diesel	$25,839	N/A
SI ICE E85	$23,491	N/A
IS HEV	$25,561	N/A
IS PHEV16	$26,150	$300
*IS PHEV56**	*$27,297*	*$300*
OS PHEV56	$29,885	$300
FCEV	$30,264	N/A
*REEV116**	*$29,907*	*$300*
BEV145	$27,057	$0
BEV338	$43,056	$0

* added vehicles – see text

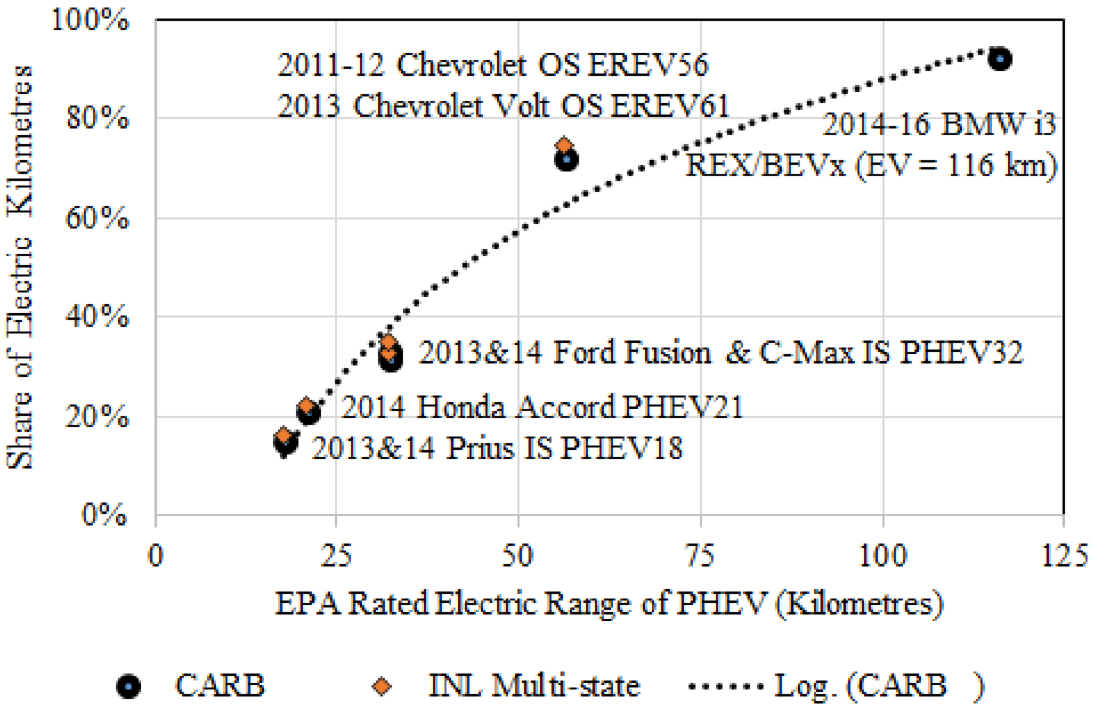

Fig. 3. Share of eVKT by PHEV/REEV type [5]

For the PHEV16, the assumed share of eVKT in [2] was 25%. However, based on [5], these PHEVs were seldom plugged in, so our estimated eVKT for this technology dropped to 16% (Table 2). It is worth noting that, although these PHEVs were seldom charged, their HEV operating efficiency was nearly as good as the pure HEV counterpart. While these PHEV16s did not plug-in frequently, they were driven far more miles per year than any other PHEV/REEV type. This was also true for the Ford Energi PHEVs. Thus, there is a possibility that even a short-range PHEV plug-in can provide fuel savings benefits, essentially by making the HEV more marketable. In fact, German manufacturers have, in effect, widely adopted this strategy, offering short range PHEV powertrain options without offering any HEV option (see fueleconomy.gov).

This illustrates that, in PHEV design, there is a fuel efficiency and customer driving behaviour balancing act that influences LCD. The IS system combined with a relatively small battery pack proves quite effective as an HEV. However, as the pack size increases, vehicle mass increases, reducing net HEV efficiency. Electric machinery power and mass is also increased to allow all-electric operations in all conditions. While reduction of all electric range in PHEVs led to more total kilometres driven, BEVs reductions in range led to less kilometres driven. The Tesla BEVs were driven an average of 21,712 km/yr while the four PHEV types in the lower left of Fig. 3 had an unweighted average of 23,934 km/yr. The Volt had a 19,956 km/yr average, which is less than the PHEVs that were more efficient in highway driving.

The least efficient and least VKT “PHEV” was the BMWi3 REX. It only averaged 14,582 km, 14% more than its BEV counterpart. The city BEV annual kilometres driven varied from 12,737 to 16,563, with an unweighted average of 15,181 km. These results certainly support the argument that limited total range makes the use of these PEVs (REEV and BEV) for intercity travel unlikely, limiting the total marketability of such vehicles. The BMW i3 BEV and BEVx were the smallest of the PEVs. These were clearly intended for urban use. Their annual km driven were the least of any PEV within the same class (BEV or PHEV).

Table 2. Kilometre share on electricity vs. gasoline for base and urban-only cases

Kilometer share for base case					Kilometer share for urban-only case			
Powertrain type	Home-to-home (LA92 Cycle)		Other (US06 Highway)		Home-to-home (LA92 Cycle)		Other (US06 Highway)	
	Electric	Gasoline	Electric	Gasoline	Electric	Gasoline	Electric	Gasoline
Gasoline SI ICE	No	75%	No	25%	0%	100%	0%	0%
IS HEV	No	75%	No	25%	0%	100%	0%	0%
IS PHEV16	16%	59%	0%	25%	21%	79%	0%	0%
IS PHEV56	70%	5%	0%	25%	94%	6%	0%	0%
OS PHEV56	70%	5%	0%	25%	94%	6%	0%	0%
SeriesREEV116	75%	0%	10%	15%	99%	1%	0%	0%
BEV145	-	-	-	-	100%	0%	0%	0%
BEV338	75%	0%	25%	0%	100%	0%	0%	0%

Based on these annual kilometres driven results, we adopted the use of a much lower annual kilometres value for the BEV145. For this paper, we assume that it cannot meet mass market needs of typical U.S. consumers, and thus left it out of the comparisons with other mass market vehicles (Table 2). The share of eVKT for the BMW i3 REX in [5] at 92%, was relatively high. Clearly, the intent of regulators to hobble this design for HEV mode operation worked. The REEV that we use to replace the BEV145, a REEV116, comes with a full sized fuel tank and keeps the battery at a higher state-of-charge than the BMWi3 REX when operating in HEV mode for long distance travel. Given the large battery pack of this REEV, we assume that owners will find it desirable to charge the pack on long distance trips (Table 2). However, since it would be more capable of long distance travel than the BMWi3 REX, we assume that the eVKT share will be 85%, primarily due to more HEV driving. An interesting insight provided by the CARB’s records of BMW i3 vs. i3 REX annual driving distances is that the total eVKT of the REX/BEVx (13,445 km) was actually higher than for the i3 BEV (12,737). The REX nationally in 2014 was also more marketable than the i3. It garnered 66% of sales in states other than Georgia (which had incentives only for BEVs) and California [15]. Thus, extension of range well beyond that of the BEV145 is necessary to suit the mass market driver in the U.S.

6.4 Gasoline and electricity consumption per 100 km

Fuel and electricity consumption estimates for local and intercity driving in this study (Table 3) are generally lower than used in [2]. For usual local home-to-home driving, we used LA92 driving cycle simulations. For intercity driving, we used US06 Highway driving cycle simulations. Driving cycle details are found in [16]. Fuel and electricity consumption values were compared to available comparable 2017 model year "best case" PEVs in the U.S. As discussed in section 4, these comparisons indicated that the on-road fuel consumption estimates derived from [1] more closely reproduced results for actual vehicles available in 2017 than did estimates developed via fuel economy adjustment formula in [2]. For the progression of increasing all-electric capability from the PHEVs to the REEV and BEV145, the estimated electricity consumption per VKT declines. Gasoline consumption from PHEVs to REEV, on the other hand, increases.

Table 3. Estimated fuel and electricity consumption for electrified vehicle revisions

	Home-to-home (LA92 Cycle)		Other & intercity (US06 Highway)	
Powertrain type	Electric (Wh/km)	Gasoline (liters/100 km)	Electric (Wh/km)	Gasoline (liters/100 km)
Gasoline	No	6.97	No	6.01
HEV	No	4.00	No	5.25
PHEV16	165	3.73	232	5.10
PHEV56 IS	149	3.80	214	5.23
PHEV56 OS	144	4.76	182	5.31
REEV116	140	6.43	180	7.79
BEV145	135	No	174	No
BEV338	156	No	189	No

6.5 Gasoline and electricity prices

Our gasoline prices are unchanged from those used in [2]. For petroleum gasoline, the cost was \$0.64/litre, while the cost of biogasoline via pyrolysis was \$1.10/litre. However, residential electricity prices are reduced by 30%, assuming early morning charging using low power "level 1" 1.4 kW electric vehicle supply equipment and circuits typical of household plugs in the U.S. The resulting "gasoline litres equivalent" price for wind would be about \$0.84/litre, and for natural gas combined cycle electricity without CCS about \$0.78/litre. The cost effectiveness benefits of this charging strategy are explained in [13] and are beyond the scope of discussion here. The effects of early morning charging, combined with opportunity of daytime charging, have been evaluated nationally in [17]. The resulting long run change in amount and mix of electric generation that would result from such a charging strategy, compared to three other alternatives, is shown in Fig. 4. Among the four charging strategies evaluated in [17], the early morning charging led to the greatest share of renewable energy ─ predominantly wind. Combined cycle natural gas – the cleanest generation technology using fossil fuels ─ provided the rest, but its share was least among the four strategies evaluated. This charging strategy is not only effective for capture of wind generated electricity, but also is effective in terms of maximizing the utilization of existing combined cycle natural gas without requiring construction of new fossil generators. If this charging pattern is used regularly (every day) by consumers with low power charging lasting several hours per night (for most PEVs), this will also improve capacity utilization and minimize the cost of additional infrastructure, enabling lower costs for all ratepayers. [18] estimated that if utilities were able to sell residential electricity at current rates, utility ratepayers and investors could obtain a large windfall. However, [18] did not assess sharing of the windfall with PEV customers, as recommended in [13]. Examination of the details in [18] implied that PEV customers would have net losses unless they were granted lower rates. A sensitivity analysis implied that enough of the windfall could be shared with PEV customers (supporting cost-shared EVSE installation) so that both utilities and PEV customers could enjoy net benefits. This occurred when residential electricity prices were reduced by 30%. Accordingly, in the revised estimates presented here, overnight residential electricity prices are assumed to be lowered by 30% for PEV owners.

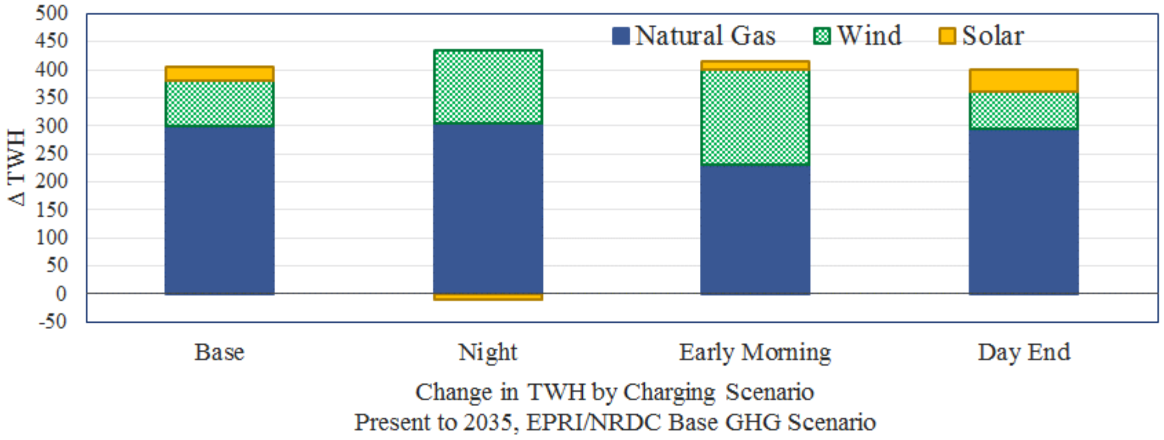

Fig. 4. Long-run change in amount and mix of generation with high BEV success, 4 charging strategies [17]

7 Results

7.1 Driving patterns comparable to averages for new U.S. vehicles

Fig. 5 shows the results for the mass market case. The new IS PHEV56 now has the lowest LCD. The cost ranges are bracketed by error bars. Though slightly higher on average, the estimated cost ranges for LCDs of HEVs, PHEV16s and the REEV116 overlap the IS PHEV56. Touching the top of the range are the SI ICE using biogasoline or E85, and the OS PHEV56. The SI gasoline uncertainty range is wide, with some overlap with all of the above. The FCEV and BEV338 are estimated to be more costly than other vehicles. Should markets for PEVs expand, these results imply that the mass market solution would involve using liquid fuels for intercity travel. The high costs of the BEV338 primarily result from adding costly larger battery pack to enable intercity driving. The results imply that it would be far less expensive to rely on liquid fuels for this function. To incorporate renewables for intercity travel, the use of renewable ethanol or gasoline is desirable. To incorporate renewables for intra-city urban travel, these estimates imply that continued pursuit of plug-in electric drive with charging strategies designed to harvest wind would become cost effective in 2025-30.

7.2 Driving patterns for intra-urban driving with no long distance intercity driving

Fig. 6 presents results for driving patterns of intra-urban driving with no long distance intercity driving (urban only case). In this case the BEV145 is the least expensive unconventional option, consistent with findings in [1], competing with conventional gasoline. The IS PHEV56 remains the low LCD cost PHEV. The cost competiveness of the IS PHEV56 arises from its lower peak electric power when operating in battery charge depletion mode. That low power level is adequate for everyday mass market urban driving, including fairly aggressive accelerations. Acceleration capability in electric only mode is far better than a transit bus. Given the potential for financial success of both the BEV145 and IS PHEV56, urban areas with air quality pollution problems still have an incentive to pursue ZEV technology, including management of timing and aggressiveness of intra-urban PHEV operations so that ZEV operation can be realized.

7.3 Caveats

7.3.1 High performance luxury vehicles

While the revised mass market investigation implies that the BEV338 cannot be cost effective, niche markets for this technology may exist. In particular, the high performance luxury vehicle market has already demonstrated the potential for success. The vehicle simulations and cost estimates in [1] and [2] were based on simulations of powertrains with acceleration capabilities less than for the average U.S. vehicle. To do a fair comparison for the high performance luxury market, an entirely different set of simulations would be necessary and is beyond the scope of this simple re-examination. For SI gasoline ICE vehicles, there is a significant fuel consumption penalty associated with engines capable of extremely fast acceleration [19]. Regardless of any simulation, the current marketplace implies that the BEV338 with powerful electric machines can compete with high performance luxury gasoline vehicles. This is good news to the extent that the market helps advance the electric powertrain technology. However, using engineering and economic judgment about the attributes of batteries and motors, the original and revised results for [2] imply that success of BEV338s in high performance luxury markets may not scale down to mass market success.

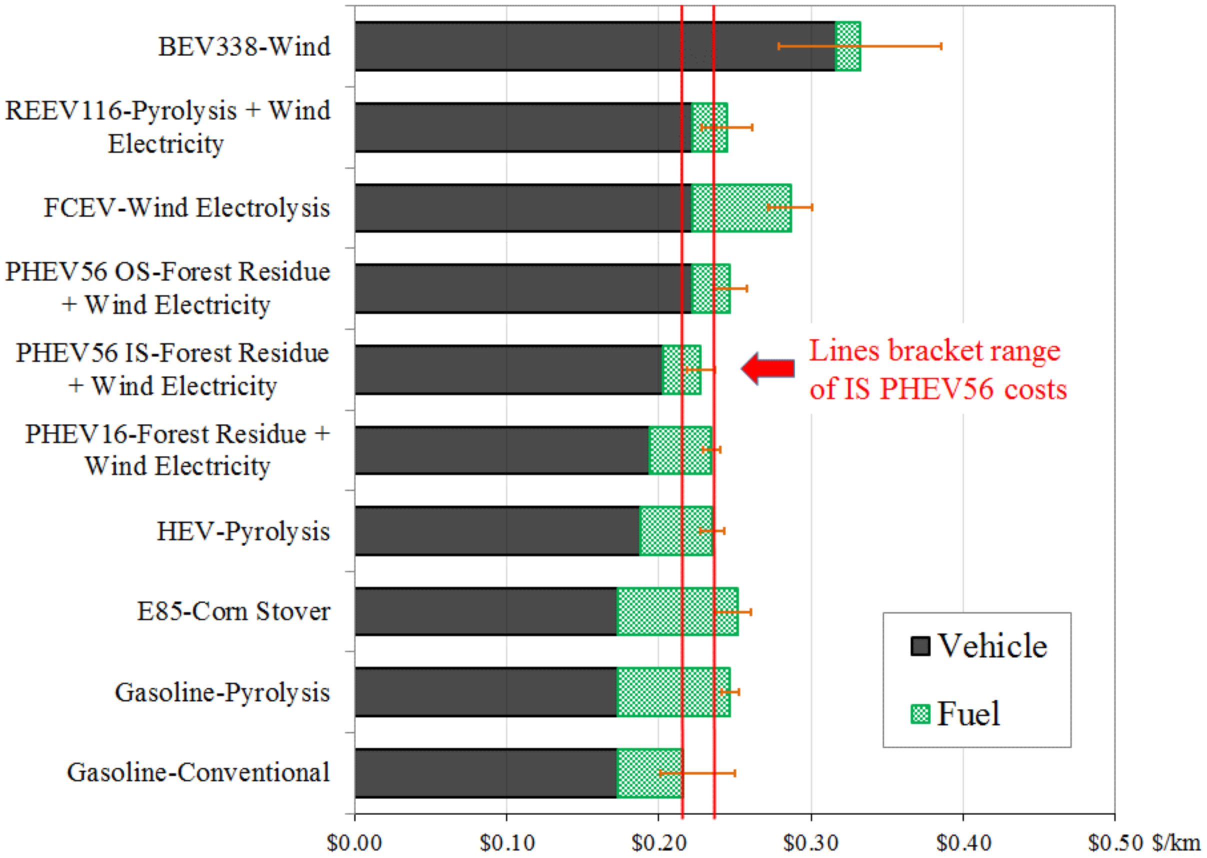

Fig. 5. Revised LCD estimates for selected powertrains from [2] along with an IS PHEV56 and REEV116. Base Case (5-year analysis window; 5% discount rate)

7.3.2 Shared use vehicles

Shared use vehicles have the potential to reduce LCD sharply by increasing daily hours and miles of operations of BEVs, allowing them to better take advantage of low fuel costs. Such markets will be evaluated in future work. However, this may still be a niche market that will not scale to mass market application in the 2025-30 time frame.

7.3.3 Full vehicle life cycle considerations

The comparisons in Figs. 5 and 6 are based on the short range perspective of new vehicle consumers, who must be satisfied if there is to be a market. However, full life cycle results for 15 years, including used vehicle use, which were included in analyses in [2], are also important. Full vehicle life cycle comparisons are relevant to long-term economic policy regarding achievement of energy independence and energy security [20, 21]. Cost-effective implementation of high octane gasoline bio-blendstocks, along with electricity from wind, solar and natural gas would enhance the odds of achieving U.S. energy independence and possibly even contribute ultimately to net exporting of crude oil and petroleum products.

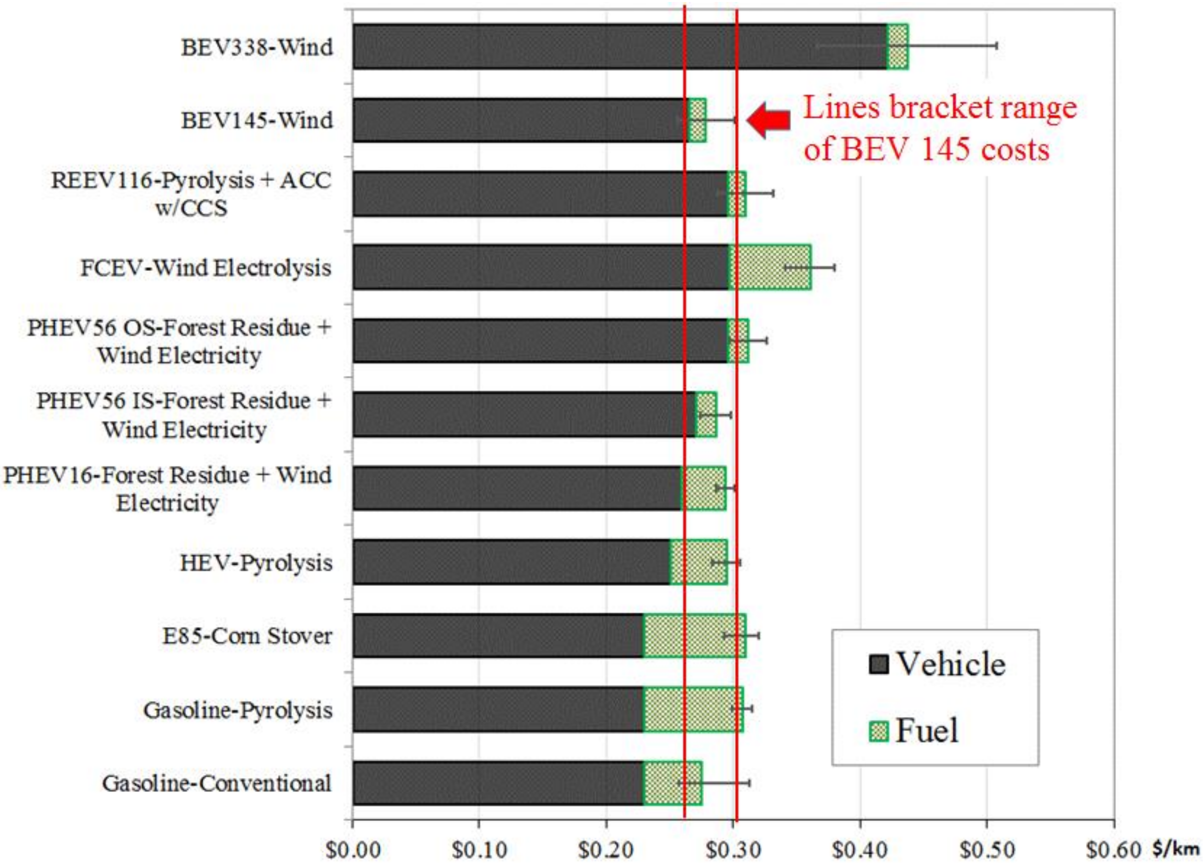

Fig. 6 Revised "urban only" LCD estimates for selected powertrains from [2] along with an IS PHEV56 and REEV116. Base Case (5-year analysis window; 5% discount rate)

8 Conclusion

This re-evaluation of [1] and [2] results changes the perspective on the best strategy for enabling renewable energy to provide VKT. When LCD results from [2] were re-evaluated in the base case (intercity driving) to compare two additional electrified powertrains, the added IS PHEV56 had the same cost as the advanced conventional vehicle using gasoline and the lowest LCD of any alternative to the gasoline vehicle. The added REEV116 also had a LCD cost almost identical to the HEV and PHEV16, with the LCD cost range overlapping that of the IS PHEV56. For urban only driving case, the BEV145 had the same LCD as the advanced conventional vehicle using gasoline and the lowest LCD of any alternative to the gasoline vehicle.

Regarding introduction of renewable energy in light duty transportation, revised results imply that inclusion of significant plug-in electrified driving using early morning charging strategies that tap into renewable electrical energy (predominantly wind) would enhance system cost effectiveness relative to relying alone on introduction of biofuels in advanced conventional powertrains with limited plug-in electrification.

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