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Cost and energy performance of advanced light duty vehicles: Implications for standards and subsidies

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ABSTRACT

This paper reviews recent literature concerning the expected future cost and energy intensity of advanced internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell vehicles (FCVs), and battery electric vehicles (BEVs). An extensive analysis is performed of a comprehensive, simulation-based dataset of feasible vehicle characteristics, performance and cost as projected to 2045 by Argonne National Laboratory. Two economic metrics, the net present value and total cost of ownership, are projected. An advanced HEV would require 3–4 times less fuel per km driven in urban driving than today's ICEV, and 2–3 times less in highway driving. Advanced PHEVs in electric mode and advanced BEVs would require about 10% the energy (as electricity) per km that today's ICEVs use (as fuel). HEVs are close to cost-competitive today while PHEVs and BEVs require large subsidies. Rather than subsidizing or mandating the early market uptake of PHEVs and HEVs, a better strategy would be to rapidly increase automobile fuel efficiency standards to that which can be achieved only with HEVs, with modest support for PHEVs, followed by the support for energy efficient fuel cell-PHEVs and/or BEVs if technological developments necessary for century time-scale sustainability are achieved.

1. Introduction

To have only a 66% chance of keeping global mean warming below 2 °C above the pre-industrial mean – the target adopted at the 2015 Paris conference (UNFCCC, 2015) – requires that net anthropogenic CO_2 emissions fall to zero by 2060–75 (Rogelj et al., 2015). Among the options available to obtain deep reductions in emissions from light duty vehicles (LDVs: cars, SUVs and pickup trucks) are reductions in the energy-intensity (MJ per vehicle-km driven, MJ/vkm) within a given drive-train class; shifts from conventional internal combustion engine vehicles (ICEVs) to vehicles with alternative drive trains (hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel-cell vehicles (FCVs), and battery-electric vehicles (BEVs, having an all-electric drive train)); and shifts from oil products to biofuels or hydrogen to satisfy any remaining fuel requirements after various combinations of the preceding options have been implemented. A shift from ICEVs entirely to HEVs could, by 2050, reduce fuel requirement per km driven by a factor of 3–4 for urban driving and by a factor of 2–3 for highway driving. A shift to PHEV drive trains, in which 2/3 or more of urban driving could be powered by grid electricity, would greatly reduce but not entirely eliminate the need for oil while minimizing the required size of batteries and vehicle charging power draw. Once the electricity grid supplying the electricity for PHEVs is fully decarbonized, there would be a corresponding decrease in CO_2 and other GHG (greenhouse gas) emissions. The final elimination of LDV GHG emissions could be achieved through some combination of (i) utilization of biofuel to meet the residual oil demand, (ii) utilization of hydrogen produced from C-free sources in fuel cells in HEVs or PHEVs (referred to as FC-HEVs and FC-PHEVs, respectively), (iii) reliance on battery swapping to get the necessary range for inter-urban travel using BEVs, or (iv) transitioning to fully electric LDVs with a sufficiently dense network of fast-recharging stations.

The government policy emphasis recently has been on promotion of electric vehicles (EVs), namely, PHEVs, FC-PHEVs, and especially BEVs. Although higher automobile fuel efficiency standards have been mandated for the next decade in many jurisdictions (reviewed in Harvey, 2017a), current standards fall far below the expected longer term efficiency potential and so will need to be significantly strengthened in a timely manner so as to maintain a steady and rapid pace of efficiency improvements. Furthermore, many standards contain a significant loophole in that BEVs are counted as having zero GHG emissions (valid where and when the electricity grid is decarbonized), and each BEV sold may count for up to 5 conventional vehicles when computing corporate average fuel economy for purposes of verifying compliance with regulated average fuel economy or CO_2 emissions (Harvey, 2017a).

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The purpose of this paper is to address what the author regards as an undue emphasis on the promotion of EVs, to the exclusion of much more stringent across-the-board improvements in LDV fuel economy than currently enacted. To do this, this paper assesses the economics and energy performance of advanced ICEVs, HEVs, PHEVs, FC-PHEVs, and BEVs. The vehicle economics depend on the vehicle purchase and operating cost relative to a baseline vehicle, the latter depending on absolute energy use of different vehicle technologies, energy costs, and annual distances driven. The analysis draws upon an extensive dataset of vehicle characteristics, simulated energy use, and projected costs of advanced vehicles over the 2015–2050 time frame produced by Argonne National Laboratory in the US. To provide context, present government EV targets and subsidies, and other recent studies of the expected cost and performance of advance vehicles, are first reviewed.

2. Government targets and subsidies for EVs

Governments around the world see EVs as a significant part of future automobile transportation, and have been backing this vision with targets and substantial subsidies aimed at moving the market toward those targets. The German government had set a goal of 1 million EVs on the road by 2020, although as of 2015 there were only 20,000 EVs in use in Germany (Bubeck et al., 2016). In May 2016 the German government began to provide subsidies of 4000€ for a BEV and 300€ for a PHEV (Bubeck et al., 2016). As of mid-2017, the US Federal government provided a tax credit of $2500–$7500 for the purchase of a PHEV or BEV, the amount depending on the battery capacity (IRS, 2017). Various US state governments require that a certain fraction of LDV sales be zero-emission vehicles by various times in the future, and various states subsidize the purchase of PHEVs or BEVs (Yuksel et al., 2016). Noori and Tatari (2016) summarized various then-existing state-level subsidies in the US; these ranged from $500–2500 for PHEVs, $1000–4000 for EREVs, and $3000–7500 for BEVs, and are in addition to federal-level tax credits. In Canada, the Ontario government released a Climate Action Plan that includes subsidies of up to Cdn$14,000 for the purchase of a BEV. In Quebec, 3.5% of new-car sales are required to be PHEVs, BEVs or FCVs by 2018, 6.9% by 2020, and 15.5% by 2025, spurred on by government rebates of up to $8000 per vehicle (Lambert, 2016; Marowits, 2017).

As a result of the California Zero Emission Vehicle Standard, it was expected (Greene et al., 2014) that manufactures would sell 6000–7000 FCVs, 20,000 BEVs, and 80,000 transitional zero emissions vehicles (TZEVs, mostly PHEVs) in California and Section-177 states during the period 2015–2017. Through to 2025, the California Air Resources Board (ARB) was expecting almost 1 million TZEVs, 385,000 BEVs, and 170,000 FCVs to be sold. Actual sales of all electric vehicles (PHEVs, BEVs and FCVs) totalled 68,000 in 2016 but appear to be on track to meet a revised target of 8% of total sales by 2025 (Reichmuth, 2017). China has adopted targets of 8% of new-car sales as zero-emission vehicles by 2018 and 12% by 2020 (Lambert, 2016). Major incentives for EV sales in China include the offering of free licence plates in place of a complex auctioning system, under which plates sell for about $12,000 each, and exemption from weekly driving restrictions (Wang et al., 2017). WA (2016) summarized EV incentives of various kinds in several countries, but did not include among the list of incentives the formulation of LDV fuel economy or CO_2 emission standards in many countries such that EVs are counted as 2–5 conventional vehicles when computing fleet averages – a provision that provides incentives to automakers to sell EVs by weakening the average fuel economy of the gasoline (or diesel) vehicles that must be achieved (Harvey, 2017a).

3. Present cost and recent assessments of the future cost of advanced vehicles

Recent reductions in the costs of batteries, fuel cells and other components of advanced vehicles have exceeded some of the most optimistic early forecasts (listed by Wu et al., 2015), so only the most recent literature is summarized here.

Table 1
Recent list prices or range of list prices of different types of LDVs. MSRP = manufacturer's suggested retail price.

MSRPs (US$) from Table 3 of Noori and Tatari (2016)						
	Current absolute cost		Cost premiums			
	Min	Max	Min	Max		
ICEV	18,710	20,245				
HEV	22,041	24,349	3331	4104		
PHEV	29,810	32,707	11,100	12,462		
BEV	31,812	35,318	13,102	15,073		
2015 list prices (US$) from Table 1 of Coffman et al. (2017)						
	ICE	HEV	PHEV	BEV		
Ford Fusion	22,744	26,701	34,482			
Ford Focus	19,215			29,995		
Ford C-Max		24,942	32,050			
Toyota Prius		24,559	31,368			
Toyota Camry	23,408	27,034				
Honda Civic	19,521	25,056				
Estimated 2014 retail prices from Table S4 of Wu et al. (2016)						
	Absolute cost			Cost premium		
	Low	Medium	High	Low	Medium	High
ICEV						
Small	7584	11,435	30,220			
Medium	13,297	20,049	52,987			
Large	16,106	24,284	64,179			
HEV						
Small	11,436	14,712	27,645	3852	**3277**	− 2575
Medium	18,471	24,481	48,302	5174	**4432**	− 4685
Large	22,602	29,809	56,955	6496	**5525**	− 7224
PHEV						
Small	17,242	23,361	34,118	9658	**11,926**	3898
Medium	26,990	35,434	55,288	13,693	**15,385**	2301
Large	32,380	43,013	64,554	16,274	**18,729**	375
BEV						
Small	20,319	27,410	38,797	12,735	**15,975**	8577
Medium	28,341	39,396	60,147	15,044	**19,347**	7160
Large	34,357	47,885	70,891	18,251	**23,601**	6712

Table 1 presents some recent compilations of the recent (2014–2015) retail cost of HEVs, PHEVs and BEVs in relation to conventional (ICEV) vehicles. For medium cost ICEVs, the recent cost premium has been around $3000–5000 for HEVS, $12,000–19,000 for PHEVS, and $13,000–24,000 for BEVs. For high-end baseline ICEVs, the cost premiums for the alternative drive trains have been lower, presumably because the larger profit margin of high-end vehicles has allowed retailers to absorb some of the extra cost.

Table 2 presents projections of the future cost of advanced vehicles, including advanced ICEVs, by Seixas et al. (2015), Thiel et al. (2016), and NRC (2013). The first two used a progress-ratio approach to project future costs, whereby costs fall by a fixed percentage (the learning rate) for each doubling of cumulative production. The relative costs of different vehicles in the future therefore depend on their starting costs and differences in cumulative production, which can be influenced by government policy, as well as the assumed learning rates. Thiel et al. (2016) considered the impact of learning rates applied to batteries ranging from 5% to 15% (but the same in all EVs), with costs for a 10% rate shown in Table 2. Seixas et al. (2015) projected a significant cost premium of PHEVs, FC-PHEVS and BEVs relative to ICEVs even in 2050, while Thiel et al. (2016) project that PHEVs and BEVs but non FC-PHEVs could cost *less* than an advanced HEV by 2030. NRC (2013) projected – using a combination of published literature and expert judgement – that FCVs and BEVs will be slightly less expensive than comparable ICEVs by 2050 (and possibly by 2030 in the case of FCVs), with HEVs only 2% ($600) and PHEVs only 6% ($1800) more expensive than ICEVs by 2050. Greene et al. (2014) explain this by noting that the cost of battery-electric and fuel-cell drive trains decreases more directly with decreasing required power than ICE drive trains, so load reductions benefit FCVs and BEVs more than ICEVs. Earlier, Weiss et al.