Energy Policy 146 (2020) 111760

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

Rethinking electric vehicle subsidies, rediscovering energy efficiency

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ARTICLE INFO

Keywords:
Battery electric vehicles
Automobile fuel intensity
Automobile fuel economy standards

ABSTRACT

Existing regulations regarding fuel energy intensity (MJ/km, litres/100 km, or its inverse, miles per gallon) of light-duty vehicles (LDVs: cars, SUVs, and pickup trucks) for 2025 or 2030 either fall short of the longterm technical potential, or contain numerous loopholes that undermine their effectiveness. At the same time, governments are subsidizing the purchase of electric vehicles (EVs) while the market share of SUVs and pickup trucks grows. This paper reviews the feasible fuel and/or electricity energy intensity of LDVs, and argues that the severity of impending anthropogenic global warming merits a strong policy approach that (i) prescribes significant improvements in the energy intensity of non-electric LDVs and plugin hybrid EVs (PHEVs) *when running on fuel*, (ii) is independent of the number of electric vehicles sold, and (iii) is accompanied by an overall limit on fleet-average CO_2 emissions that applies to all manufacturers irrespective of the average size and mass of vehicles sold. Subsidies for EVs should be scaled back or eliminated, relying instead in the near term on deep across-the–board improvements in the fuel efficiency of LDVs that will have beneficial spillover effects on the eventual energy intensity of EVs and mineral requirements following a delayed market scale-up.

1. Introduction

Electric vehicles (EVs), consisting of plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs), are widely seen as an effective means of reducing greenhouse gas emissions from light-duty vehicles (LDVs: cars, sport-utility vehicles (SUVs) and pickup trucks), and many environmental groups are advocating stronger government support of EVs with little or no mention of the need to mandate further across-the-board increases in the fuel economy (litres/100 km or miles per gallon (mpg)) of the LDV fleet.[1] Such efficiency improvements as are mandated often fall far short of the technical potential to improve automobile fuel economy thought to be achievable with ongoing research and development, and are less stringent for heavier vehicles. This works to the advantage of most automobile companies, who make larger profits selling large vehicles (SUVs and pickup tracks) rather than smaller vehicles (Kwak, 2009; ZumMallen, 2017), and who have consistently opposed more stringent fuel economy standards.

PHEVs and BEVs are currently substantially more expensive than conventional vehicles (CVs), so many governments around the world have been providing substantial subsidies in order to promote sales of EVs; examples are given in Table 1. These subsidies have led to a rapid growth in EV sales, as shown in Fig. 1, with global sales reaching 2.1 million/yr in 2018 and cumulative sales reaching 5.3 million by the end of 2018. China accounted for about half of global EV sales in 2018, but its subsidies of EVs were scheduled to end in 2020, with an uncertain impact on future sales (Li et al., 2018). Global automobile sales were stable at 79 million/yr over the period 2016–2018, so the 2.1 million EV sales in 2018 represented 2.7% of the global market.[2] Bloomberg New

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[1] For example, the *Environmental Platform Asks* (https://environmentaldefence.ca/wp-content/uploads/2019/05/EnvironmentalPlatformAsks_2019Election_FINAL.pdf, accessed on 26/6/2019), a joint request to Federal political parties from 14 Canadian environmental groups, calls for "regulations that require vehicle manufacturers [to] sell an increasing percentage of their fleet as Zero Emission vehicles …. Starting with 10% ZEV sales by 2025, 30% by 2030, and 100% by 2040, while taking additional steps to make ZEVs more affordable". The latter part of the request could mean subsidies. The *Green New Deal* resolution presented by Congresswoman Alexandria Octavia-Cortez calls for "zero-emission vehicle infrastructure and manufacturing" (Paragraph (2) H (i)) with no mention of increasing automobile fuel economy as an intermediate step. (see H.Res.109 - 116th Congress (2019–2020): Recognizing the duty of the Federal Government to create a Green New Deal. Accessed on 25/6/2019).

[2] Within the EU, BEVs accounted for 0.6% of new car sales in 2017 and PHEVs 0.8%, and HEVs an additional 2.7% (EEA, 2018); in the US, the shares were 0.6% BEV and 0.8% PHEV in 2017, increasing to a projected 1.8% BEV and 0.9% PHEV in 2018 (EPA (2019, Fig. 4.13); within China, combined BEV and PHEV sales reached 1.07 million in 2018 (according to https://wattev2buy.com/global-ev-sales/ev-sales-graphs/) out of total LDV sales of 28.08 million (according to https://www.marklines.com/en/statistics/flash_sales/salesfig_china_2018), or 3.8%.

https://doi.org/10.1016/j.enpol.2020.111760
Received 17 July 2019; Received in revised form 1 July 2020; Accepted 11 July 2020
Available online 3 September 2020

Table 1
Selected financial incentives for EVs, from Stephens et al. (2018) for all cases except China, which is taken from Du et al. (2018, Fig. 13). All amounts outside the US are in approximate US$.

Region	Incentive	
United States		
Federal	Tax credit of up to $7500/EV	Cancelled
California	Tax credit of up to $2500/BEV, up to $1500/PHEV	
New York	Tax credit of up to $2000/EV	
Europe and China		
France	Rebate of $7230/BEV	
Germany	Rebates of $3600/PHEV and $4820/BEV up to a maximum of 400,000 cars	Program ends in 2020
Netherlands	Exemption from CO2-based component of registration tax and from annual ownership tax	
Norway	BEV exception from VAT of 25% and from 1-time registration tax of up to 25% of purchase price	
Sweden	Rebate of up to $7230/BEV	
UK	Rebates of $3400/PHEV and $6000/BEV plus exemptions from annual ownership taxes and from London's congestion fee of $4100/year	
China	Federal, state and automaker subsidies amounted to about 2/3 of the vehicle cost over the period 2013–2015 in some cases	

Energy Finance expected global BEV + PHEV sales to rise to 10 million in 2025, 28 million in 2030 and 56 million by 2040, when they would constitute 57% of all passenger vehicle sales and 30% of the fleet (BNEF, 2019). Of the 56 million EVs sales projected for 2040, 50 million would be BEVs and 6 million would be PHEVs. Others are more cautious, with EIA (2017) projecting a market share in the US in 2050 for HEVs + PHEVs + BEVs of 25%, while Ai et al. (2019) assume a PHEV + BEV share in 2040 of only 8.75%.

BEVs are inherently simpler than CVs, their high cost being largely related to the cost of batteries. Battery costs (per kWh of storage capacity) fell by a factor of six between 2007 and 2017 (Nyqvist et al., 2019) and may fall by another factor of two or three by 2030, with the result that BEVs may cost no more than CVs by 2030 or even sooner. However, the economics of EVs is more favourable for smaller than for larger vehicles (Wu et al. (2015) and Harvey (2018a)). Even after EVs reach cost parity with CVs, government support will be needed to establish an adequate recharging infrastructure (in the case of BEVs, but not for PHEVs); without it, the market share of EVs could be quite limited.

Two other significant factors related to both the life cycle cost of EVs and the environmental benefits of EVs relative to CVs are the cost and source of electricity used to charge EVs. Gasoline costs in May 2019 ranged from a low of about $0.5/litre in much of the Middle East and some developing countries (where it is subsidized), to $0.84/litre ($3.15/gallon) in the US, $1.50–2.00/litre in much of Europe, and $2.20/litre in Hong Kong (see https://www.globalpetrolprices.com/gasoline_prices/), while retail electricity costs in June 2019 ranged from $0.03–0.06/kWh in much of the Middle East (where it is again subsidized) to $0.10–0.15 in the US and Canada, and $0.15–0.35/kWh in much of Europe (see https://www.globalpetrolprices.com/electricity_prices/). Gasoline at $1.00/litre ($3.78/gallon) is equivalent to 3.14 cents/MJ, while electricity at $0.10/kWh is equivalent to only 2.78

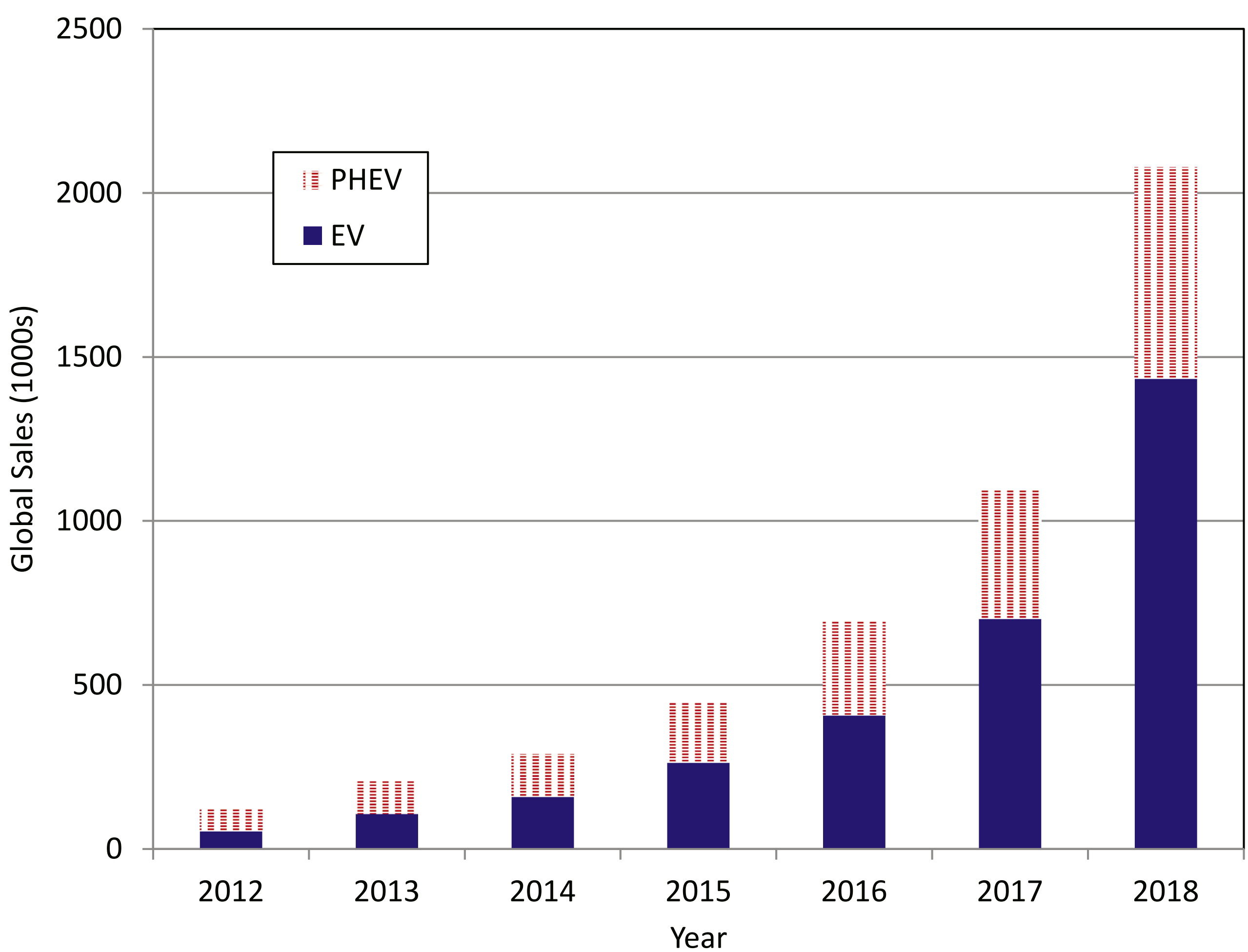

Fig. 1. Growth in worldwide sales of BEVs and PHEVs, 2012–2018. Source: BNEF (2018) for 2012–2017, wattev2buy for 2018.

cents/MJ, but electric drive trains are about three times as efficient as today's CV drive trains, so with \$1.00/litre gasoline and 10 cents/kWh electricity, EVs are over 3 times less expensive per km driven in terms of energy cost, while for gasoline at \$1.5/litre and electricity at \$0.05/kWh (see below), the cost advantage is a factor of *10*. However, most of the electricity produced in the world today is generated from either coal or natural gas. Charging EVs with electricity from coal provides little or no reduction of greenhouse gas (GHG) emissions (Yuksel et al., 2016), and this may also be the case for electricity derived from fracked natural gas, which can have equivalent or larger emissions, depending on the rate of methane leakage during fracking operations (Sanchez and Mays, 2010; Qin et al., 2017).

The real environmental promise of EVs lies in the possibility of recharging them with electricity that is derived from renewable energy sources. Breathtaking decreases in the cost of wind and solar energy have occurred during the past decade, and further large cost reductions are projected. In particular, the cost of PV (photovoltaic) solar electricity has fallen from 40 to 80 cents/kWh in the early 2000s to 3–9 cents/kWh across much of the world for 2016–2019 contracts (IEA, 2016, Fig. 4.3), while the cost of wind energy has fallen from 7 to 15 cents/kWh as recently as 2006 (Harvey, 2010), to 3–9 cents/kWh for 2016–2019 contracts (IEA, 2016, Fig. 4.3), and is), and is projected to drop to 2.0–3.5 cents/kWh in the US (Dykes et al., 2017). Costs of electricity from concentrating solar thermal powerplants (CSTP), which can be used in arid and semi-arid regions to generate electricity 24 h per day, have fallen to 12–20 cents/kWh in some regions (REN21, 2018) and are projected to reach 5–10 cents/kWh in the US (Murphy et al., 2019), which could be lower still in other sunny regions.

In spite of these positive developments, I have serious misgivings concerning the emphasis of many governments on the promotion of EVs at this time. My concerns revolve around (i) its potential to deflect attention away from the potential for large fleet-wide improvements in fuel economy compared to many current or currently-scheduled fuel economy or CO_2 emission standards; (ii) the loopholes in these standards and other features that undermine their effectiveness; (iii) the cost and environmental effectiveness of EV subsidies compared to stringent across-the-board standards related to fuel use of cars when powered by fuel; (iv) the implications for a decarbonizing electricity grid of early scale-up of relatively energy-intensive EVs; (v) the relatively high requirements for scarce metals by current EVs compared to projected decreases of metal loadings in advanced EVs, combined with the time required to development a capability for recycling of EV metals; and (vi) possible reduced overall safety due to the greater weight of EVs compared to CVs at present but not as projected in the future. The balance of this paper presents my reasons for these concerns, and concludes with policy recommendations.

2. Vehicle performance potential and regulations

2.1. Potential reductions in LDV energy use per km driven

This section presents selected results from the most recent set of simulations of LDV energy use performed at Argonne National Laboratory (Islam et al., 2018; henceforth referred to as ANL) for different drive trains and market segments (compact and mid-size car, small and mid-size SUV (sport-utility vehicle), light truck), from 2010 through to 2045, assuming either "slow" or "fast" technology development. These simulations were done with the Autonomie model, which was developed in collaboration with General Motors, has been validated against vehicle test data for several powertrain configurations and vehicle classes, and is used by over 175 companies and research entities to support the development of advanced vehicles. The years in the ANL analysis are "lab years", that is, the time when a given performance might be achieved at the lab or prototype scale; commercial availability would come perhaps 5 years later. Thus, ANL results will be designated here by the lab year plus 5 years (so, for example, 2010 and 2045 lab-year results will be referred to as 2015 and 2050 results, respectively, with the latter also referred to as "advanced"). The drive trains considered include an internal combustion engine (ICE) in a CV, and hybrid electric vehicle (HEV), PHEV and BEV drivetrains. ANL gives results for U.S. urban and highway driving under EPA test conditions along with adjusted results that are meant to represent real-world driving conditions; adjusted fuel consumption is about 25-35% higher in urban driving and 40% higher in highway driving. Unless otherwise stated, the results present here are adjusted results.

All of the results presented here are given in tabular form in the Online Supplement (Tables S1–S2), along with the corresponding adjusted results from the previous set of simulations (Moawad et al., 2016) in Table S3, and various ratios (Tables S4 and S5). Compared to the 2016 simulations, the latest simulations give a few percent greater energy use for the 2015 CV and HEV and advanced BEV, but about 20% less energy use for the 2015 BEV. The previous simulation results were used in Harvey (2018a) in an analysis of the future cost and performance of advanced vehicles and as an input to a complete lifecycle analysis by Elgowainy et al. (2018) for the 2020–2025 time horizon.

Fig. 2 compares the fuel and electricity energy intensity (MJ/km) of present-day and advanced compact cars and pickup trucks in city and urban driving under fast and slow technological development; the Fast results are ambitious targets that may or may not be achievable, while the Slow results are considered to be fully achievable with little uncertainty. In urban driving, the 2015 compact-car HEV requires only 60% the fuel per km driven as a 2015 CV – an impressive improvement - while the PHEV when operating on fuel requires about 70% that of the 2015 CV. For light trucks, the HEV fuel requirements are 64% and 78% that of the 2015 CV.[3] However, the advanced HEV is projected to require only 25–45% as much fuel as the 2015 CV for compact cars and only 30–45% as much for light trucks. In highway driving, the 2015 HEV reduces fuel use by only 10–15%, while the advanced HEV requires only about 35-65% as much fuel as the 2015 CV.

Fig. 3 compares the energy intensity across the different market segments for the 2015 CV, 2015 HEV, and advanced HEV under fast and slow development. The following fuel savings are possible in city driving for the following changes: from the 2015 CV pickup to the 2015 CV compact car, 32%; from the Advanced HEV pickup to the Advanced HEV compact car, 42%; and from the 2015 CV pickup to the Advanced-slow and Advanced-fast HEV compact car, 70% and 82%, respectively. Clearly very large reductions in fuel consumption and associated GHG emissions are possible over the next 30 years from a combination of stringent efficiency measures and some shifting from pickup trucks to lighter vehicles.

Given these results, the critical question is, What would be easier and potentially accomplished faster: a complete transition to advanced HEVs, or the transition to 70–100% EVs consisting of some mix of PHEVs and BEVs? Or, a transition to a new car fleet consisting solely of HEVs at 2015 efficiency levels, compared to a 50–60% transition to EVs? As HEVs require no new electricity infrastructure or matching of supply and demand at the same time that a transition from traditional to intermittent renewable energy sources is underway, it would seem that full-scale transition from CVs to HEVs would be the easier and faster transition.

Whatever the answer to this question, the 2015 HEV already exists; full transition to this technology achieves the same fuel savings in highway driving as roughly a 40% shift to BEVs or a 50% shift to equal proportions of PHEVs and BEVs. This would require setting fuel economy standards, applicable to fuel consumption by vehicles powered by fuel, that can be met only by the most efficient existing HEVs, with no loopholes in the form of credits from sales of EVs.

[3] Online Supplement Table S6 compares the fuel consumption of CV and HEV versions of various LDV models for the 2014 model year (assuming 55% urban, 45% highway driving). HEV fuel consumption is 26-40% less than the otherwise comparable CV, in line with the ANL simulation results for the 2010 lab year.

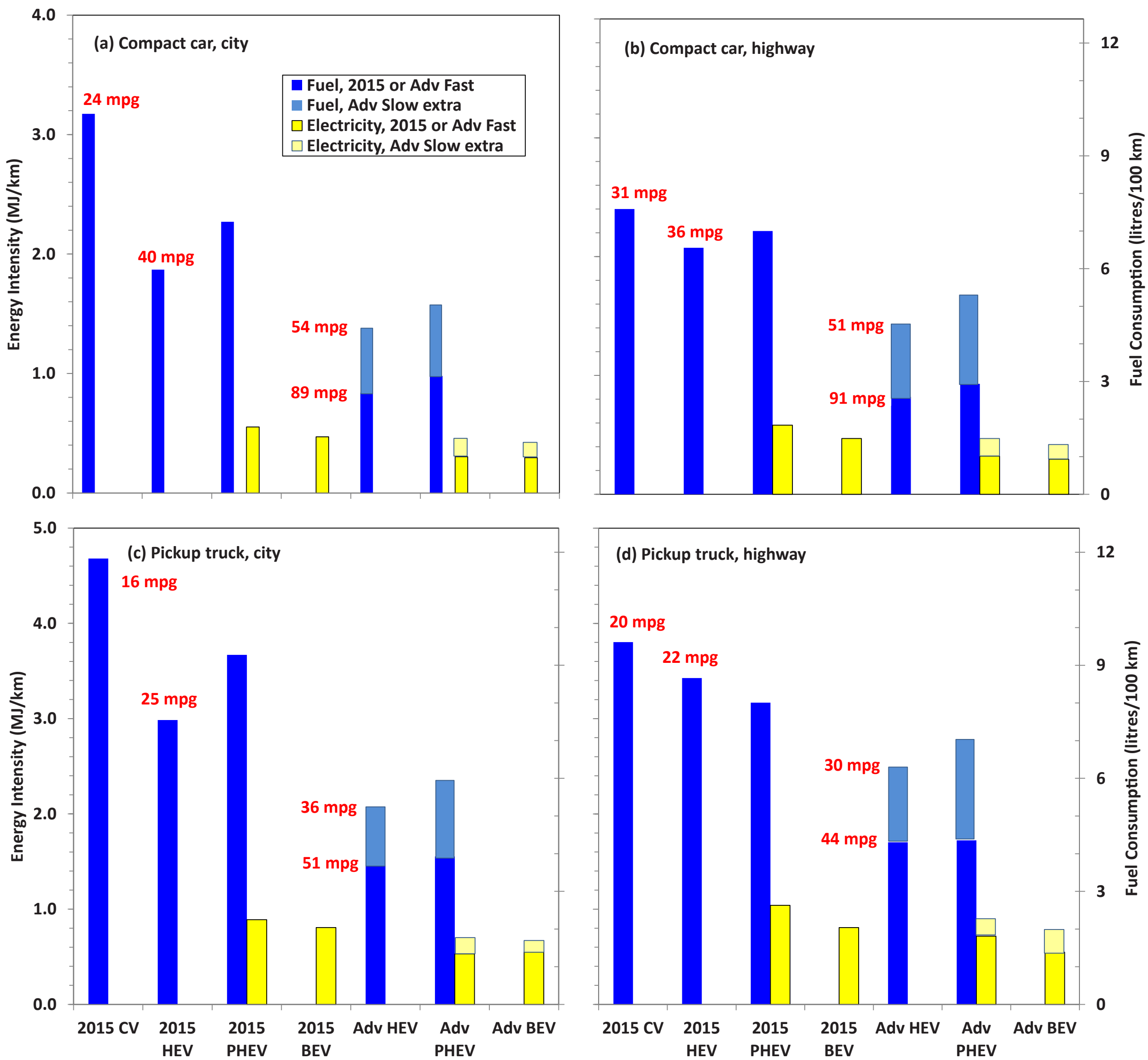

Fig. 2. Energy intensity of the 2015 CV, HEVs, PHEVs and BEVs, and of advanced HEVs, PHEVs and BEVs, as simulated by ANL. Results are given for compact cars in (a) city and (b) highway driving, and for light trucks in (c) city and (d) highway driving. For advanced vehicles, the darker band gives fuel requirements with fast technological development, while the lighter band gives the additional fuel requirement with slow technological development.

2.2. Currently mandated fuel economy improvements in the US, EU and China

In this section the energy intensity as computed by ANL for current CVs and HEVs, and for advanced HEVs under slow and fast technology development is compared with current and pending CO_2 or fuel consumption standards in the US, EU and China.[4]

2.2.1. United States

The US Environmental Protection Agency (EPA) has set separate CO_2 emission standards for “cars” and “trucks” (defined as a light truck, SUV or mini-van up to 8500 lbs gross weight) (EPA, 2012a,b) under standardized test conditions. The emission standards within each category are based on the vehicle “footprint” (the area defined by the points where the tires touch the ground), and are less stringent for vehicles with larger footprints. Manufacturers are not required to build vehicles of any particular type and are not given any incentives to do so. EPA (2012a, Table 1) has projected fleet-wide average CO_2 emissions for cars and light trucks sold in the US for the years 2016-2025 based on an assumed distribution of vehicle footprints within each category, and an overall average CO_2 emission based on a car share of total sales deviating only slightly from 66%.

Fig. 4a gives estimates of real-world average fuel economy over the period 2000–2018 as given by EPA (2019) for sedans/station wagons, car SUVs, and Minivan/Vans (regarded as “cars” here) and for truck SUVs and pickup trucks (“light trucks” here). Also given, as solid lines, is the variation in the average passenger car and truck fuel economy (miles per gallon) from 2016 to 2025, assuming that the average car and truck CO_2 emissions as measured with the test procedures comply with the emission standards. In recognition of the fact that real-world fuel economy is worse than that computed from the test procedures, EPA reports mpg values to the public (via mpg labels) that are about 20% lower than the test values (EPA, 2006), so projected mpg values reduced by 20% are shown as dashed lines in Fig. 4a.

Fig. 4b converts the adjusted standards shown in Fig. 4a to fuel consumption, and compares that with the adjusted fuel consumption for 2015 CVs and HEVs, and the range (from slow to fast development) for 2025 and 2050 HEVs, as simulated by ANL for the mid-size car and light

[4] For discussions of Japanese and South Korean LDV standards, see Anon (2018) and Oh et al. (2016), respectively.

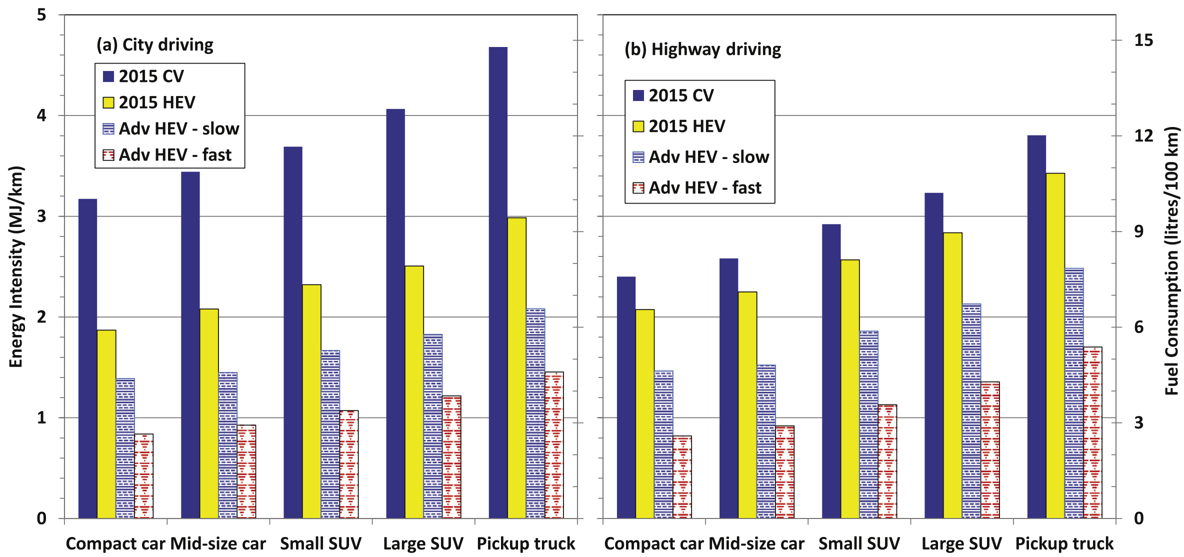

Fig. 3. Comparison of energy intensity in (a) city and (b) highway driving of different LDV market segments for the 2015 CV and HEV and the advanced HEV under fast technological development, as simulated by ANL.

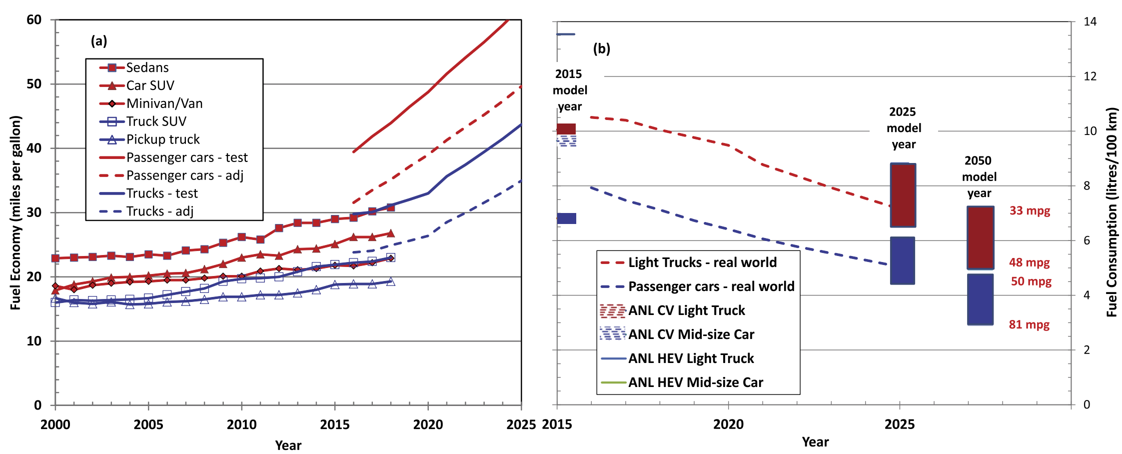

Fig. 4. (a) Estimates of real-world average fuel economy over the period 2000–2018 as given by EPA (2019) for various vehicle types, along with average permitted gasoline-equivalent fuel economy (mpg) of new cars and light trucks sold in the US for the period 2016–2025 as projected by EPA (2012a), based on permitted CO_2 emissions for cars and trucks of different sizes and the projected distribution of car and truck sizes. (b) The 2016–2015 fuel economy projections from (a), converted to fuel consumption (litres/100 km), along with ANL simulations of adjusted (upper) and unadjusted (lower) fuel consumptions for 2015, 2025 and advanced (2050) cars and light trucks. Note that, for presentation purposes, the 2050 results are not on a linear scale, and their placement exaggerates the rate of improvement needed after 2025 to reach these results. Also note that the 2015–2025 standards contain various loopholes (described later in the main text) whereas the ANL results are true fuel consumption results.

truck. As seen from Fig. 4b, the EPA 2025 standards for both light trucks and average car fall about midway between the ANL slow and fast development projections for 2025. Fuel consumption for 2050 under fast development would be about 30% lower for cars and 35% lower for trucks than under the 2025 standards, but is only slightly lower under slow development.

However, the EPA standards will be diluted compared to those shown in Fig. 4 for two reasons. First, reductions in leakage of the air conditioner refrigerant or use of alternative refrigerants with lower warming effect can be credited against the required reduction in tailpipe CO_2 emissions, reducing the required improvement in fuel economy.[5] Second, the standards apply to the average of fuel-powered and electric vehicles, with CO_2 emissions from EVs related to the generation of electricity assumed to be zero. Indeed, a multiplier credit is applied to EVs (and fuel cell vehicles, FCVs) for the period 2017–2021, whereby each EV or FCV sold counts as 2.0 cars during 2017-2020, 1.75 cars in 2020, and 1.5 cars in 2021. Third, because the standards are regarded as challenging for large vehicles, additional credits are allowed (rather

[5] The maximum allowed AC credit is 18.8 gCO_2-eq/mile for cars and 24.4 gCO_2-eq for trucks (EPA, 2012a, Section IA.2c), compared to 2025 emission standards of 143 g/mile for cars and 203 g/mile for light trucks.

than forcing manufacturers to downsize their offerings). For example, an additional credit of up to 20 gCO_2/mile is allowed during 2017-2025 for pickup trucks that use the HEV drivetrain, if the technology is used on at least 10% of a manufacturer's pickup trucks (EPA, 2012b, Section IA.4e). Of course, the use of HEV drivetrains already contributes to achieving the CO_2 target by making the vehicle more efficient, so this additional credit is equivalent to weakening the target for pickup trucks. Also note that, even without this additional credit, the overall allowed CO_2 emission increases if the fraction of large vehicles increases, because the overall target is a weighted average of size-based targets that are weaker the larger the vehicle.

To illustrate the impact of extra counting of EVs, let $\overline{E}$ be the required fleet average CO_2 emission, let f_{EV} be the EV fraction of total sales, and let M be the credit multiplier (subsequently referred to as the supercredit factor). For purposes of verifying compliance with the standard, the average emission is computed as

$$\overline{E} = \frac{E_{CV}(1-f_{EV}) + E_{EV}Mf_{EV}}{(1-f_{EV}) + Mf_{EV}} \tag{1}$$

where E_{CV} and E_{EV} are the CO_2 emissions for conventional (non-electric) and electric vehicles, respectively. As E_{EV} is assumed to be zero, the permitted average emission by non-electric vehicles is given by

$$E_{CV} = \overline{E}\,\frac{(1-f_{EV}) + Mf_{EV}}{(1-f_{EV})} \tag{2}$$

The EPA test standard for cars in 2025 (given their assumed vehicle size distribution in 2025) is 143 gCO_2/mile or 89 gCO_2/km. The real-world emission is assumed to be 33% larger, or 118 gCO_2/km. Table 2 shows the effect on the allowed E_{CV} and on $\overline{E}$ when E_{CV} is allowed to increase with increasing EV share, as well as when E_{CV} is fixed at 118 gCO_2/km, for various values of M as f_{EV} increases from 0.0 to 0.25. For $f_{EV} = 0.25$ and $M = 1.5$ (the most extreme values considered here), $E_{CV} = 178$ gCO_2/km and the true fleet average emission is 133 gCO_2/km rather than 118 gCO_2/km – about 13% larger, in spite of a 25% EV share. However, if E_{CV} is merely fixed at the 2025 value irrespective of the EV share, $\overline{E}$ decreases to 89 gCO_2/km (a 25% reduction) when $f_{EV} = 0.25$, and is independent of M. Thus, merely closing the many loopholes in the current regulations for the period beyond 2025 would deliver significant savings as the EV share increases, which would be further amplified if E_{CV} is required to decrease.

Table 2
Allowed emission (gCO_2/km) by non-EVs for various EV market shares and supercredit multipliers, and the resulting average emissions assuming zero emissions from electricity generation, given a permitted average emission in the absence of supercredits for EVs of 118 gCO_2/km.

EV market share	EV supercredit multiplier		
	1	1.25	1.5
Allowed emissions by non-electric vehicles			
0.00	118	118	118
0.05	125	126	128
0.10	132	135	138
0.15	139	145	150
0.20	148	156	163
0.25	158	168	178
Average emissions			
0.00	118	118	118
0.05	118	120	121
0.10	118	121	124
0.15	118	123	127
0.20	118	124	130
0.25	118	126	133
Average emissions with non-EV emission fixed at 118 gCO_2/km			
0.00	118	118	118
0.05	112	112	112
0.10	106	106	106
0.15	100	100	100
0.20	95	95	95
0.25	89	89	89

2.2.2. European union

Fig. 5 shows the 2017 and 2021 CO_2 emission limits in the EU, translated into litres/100 km, as a function of vehicle mass, along with the ANL Fast results for advanced HEVs. The EU goal was to achieve total fleet average CO_2 emissions of 130 gCO_2/km or less by 2017 (achieved), and 95 gCO_2/km or less by 2021, but with non-rigid targets for individual manufacturers that increase with vehicle mass, as shown in Fig. 5. The emission standard is to be reduced by a further 15% in 2025 and by 31% for vans and by 37.5% for cars in 2030 (EP, 2019). As seen from Fig. 5, the 2021 standards are slightly (for compact cars) to moderately (for light trucks) stricter than the unadjusted 2015 HEV fuel use as simulated by ANL, while the 2030 standards are comparable to the unadjusted standards for advanced vehicles under fast technological development for compact cars, and substantially more strict for light trucks. The 2030 and even the 2021 standards are so strict that they likely can be satisfied only by selling a substantial portion of EVs and counting EVs as having zero CO_2 emissions. Indeed, supercredits are given for the sale of EVs, whereby each EV sold counts as 2 cars in 2020, 1.67 in 2021, and 1.33 in 2022, subject to a supercredit cap of 7.5 gCO_2/km (EP, 2019). Manufacturers that achieve a share of zero- and low (<50 gCO_2/km)-emission (ZLEV) car sales above a benchmark of 15% in 2025 and 35% in 2030 will receive a reduction in their CO_2 target by up to 5% (EEA, 2018, p11). In addition, each ZLEV sold will count as 1.85 ZLEVs up to 2030 for manufacturers where the ZLEV share of their total sales is less than 5%.

As in the US, the EU test procedures used to verify compliance with the CO_2 emission standard underestimate fuel use compared to real-world driving conditions. For a variety of reasons discussed by Fontaras et al. (2017), the discrepancy has grown over time, reaching the point where real-world fuel consumption was about 40% greater than test consumption by 2015. This prompted the EU to switch from the original testing protocol (the New European Driving Cycle, or NEDC), to the Worldwide Hamonized Light Duty Test Procedure (WLTP). Using the WLTP, real-world fuel consumption is about 20% larger than test consumption (rather than 40% larger, because the measured test consumption is larger). Automobile companies can use the NEDC protocol for compliance purposes until 2021, at which point the WLTP protocol must be used, which increases the effort required in going from the 2017 to the 2021 standards.

Assuming, then, that future automobiles in the EU need to comply with the 2030 target using the WLTP test procedure and that the real-world consumption will be 20% larger, we see that the required real-world consumption in 2030 will be less than the real-world consumption as projected by ANL for HEVs of comparable mass in 2050 under the assumption of fast technological development. In this case, allowing some flexibility in meeting, by 2030, what ANL optimistically considered to be feasible by 2050, is justified.

2.2.3. China

Fig. 6 shows corporate average fuel consumption (CAFC) standards for vehicles sold in China, beginning with Phase I (which came into force over the period 2005–2006), through to the current standards (Phase IV) and those to come into force in 2025 (Phase V) and 2030 (Phase VI). The allowed fuel consumptions apply to the average of all vehicles in various mass classes, and are larger the greater the vehicle mass – although the ratio of the allowed fuel consumption of the heaviest vehicles to the lightest vehicles falls from 2.15 for Phase I to 1.75 for Phase VI. Also shown in Fig. 6 is the unadjusted and adjusted fuel consumption of the 2015 and advanced HEVs (with fast technology development) as simulated by ANL for the five market segments considered by ANL, plotted against the corresponding vehicle mass. In the lower part of the overlapping mass range, fuel consumption under the 2030 standard is

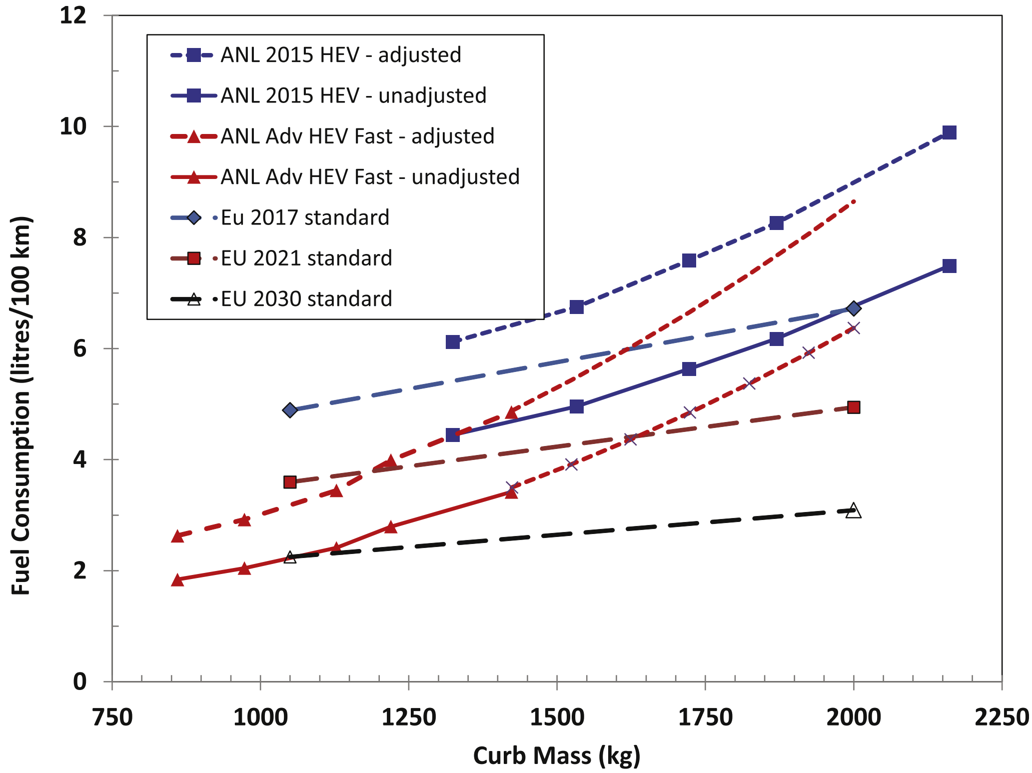

Fig. 5. Gasoline-equivalent fuel consumption corresponding to tailpipe CO_2 emissions permitted in the EU in 2017 and 2021 and proposed for 2030, as a function of vehicle mass, along with ANL simulated fuel consumption with a 67:33 city:highway weighting for advanced HEVs. Source for EU standards: REE (2016, Fig. 3.23).

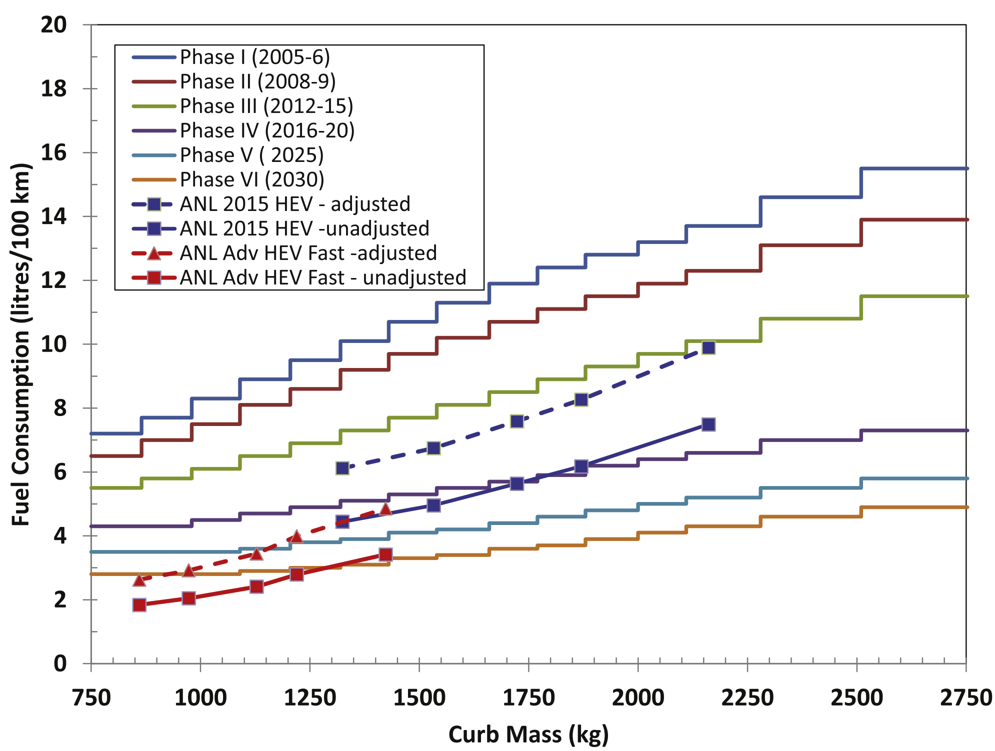

Fig. 6. Corporate average fuel consumption (CAFC) standards in China under successively later phases, as a function of vehicle mass, along with ANL simulated fuel consumption with a 67:33 city:highway weighting for advanced HEVs. Source for Chinese standards: Wang et al. (2019).

comparable to the adjusted consumption of the advanced HEV, while in the upper part of the overlapping mass range, the 2030 standard is comparable to the unadjusted advanced HEV. ZumMallen (2017) estimate that compliance with the 2025 standards will require an HEV market share of about 63% in the absence of any supercredits. The Chinese standards extend to vehicles of much greater mass than simulated by ANL (even for 2015 vehicles), so achieving the mass reductions envisaged by ANL in each vehicle market segment will make a significant contribution to reducing fuel requirements.

Using data collected under real-world driving conditions in China, Dror et al. (2019) estimate that the gap between test and actual fuel consumption grew from 12% in 2008 to 30% in 2017, such that real-world fuel consumption remained unchanged while the allowed consumption decreased by 15% (the gap is 23% for manual-transmission vehicles, 32% for automatic-transmission vehicles, and the gap tends to increase with increasing vehicle mass). Possible explanations given are inadequate vehicle maintenance, added vehicle weight, driving style, and driving conditions. As noted in Section 2.1, the ANL adjusted fuel consumption amounts are 25-35% higher in urban driving and 40% higher in highway driving than the unadjusted (test cycle) amounts, while real-word fuel consumption in Europe is 20% higher than measured using the WLTP protocol and 25% higher in the US using its testing protocol.

China allows extra credits for sales of “New Energy Vehicles” (NEVs – BEVs, PHEVs and fuel cell vehicles) and for energy-efficient vehicles (ZumMallen, 2017). Each NEV with an all-electric range of at least 50 km sold counted as 5 vehicles in 2016-2107 and 3 in 2018-2019, and will count as 2 in 2020. Separate multipliers also apply to “Fuel Efficient Vehicles” (FEVs, defined as vehicles with a fuel consumption of 2.8 L/100 km or less). For the 2021–2025 period, ZumMallen (2017) investigated the effect of credit multipliers for both NEVs and FEVs ranging from 1.0 to 6.0. For a multiplier credit of 4.0, the national fuel consumption target is diluted from 4.1 L/100 km to 5.0 L/100 km, and the implementation of advanced technology is reduced because of the less stringent standard.

2.2.4. Summary

LDV emission standards for as far into the future as have been determined (2025 or 2030) in the US, EU and China are summarized in Table 3 in terms of gCO_2/km, litres/100 km, and mpg. Also given are the unadjusted values as simulated by ANL for advanced (2050) vehicles assuming fast technological development. The EU standard for 2030 at the lowest-mass vehicle is comparable to the ANL values interpolated to the same mass, and more strict for the high-mass vehicle compared to the ANL values extrapolated to the same mass, while the Chinese 2030 standard is less strict for the lowest-mass vehicle and much more strict for the high-mass vehicle. The unadjusted ANL fuel economy values for 2050 range from 68 mpg for pickup trucks to 128 mpg for compact cars for the Fast case (and from 45 to 75 mpg for the Slow case), whereas Lempert et al. (2019) assume in their most aggressive US scenario that the fleet-average LDV fuel economy under test conditions is 62.5 mpg in 2050, comparable to the ANL Slow case.

Table 3
Summary of future LDV fleet-average standards under test conditions, or unadjusted potentials as simulated for advanced HEVs under Fast development (with Slow mpg values also shown, in brackets). The extrapolation of ANL results to 2000 kg is taken from Fig. 5.

	As gCO_2/km	As litres/100 km	As mpg
US in 2025			
Cars	89	3.8	62
Light trucks	126	5.4	44
Expected mean	101	4.3	54
European Union in 2030			
1050 kg vehicle	53	2.25	105
2000 kg vehicle	72	3.09	76
China in 2030			
860 kg vehicle	66	2.8	84
2000 kg vehicle	90	4.1	57
ANL Advanced HEV			
Compact car (860 kg)	43	1.8	128 (75)
Mid-size car (973 kg)	48	2.0	115 (71)
Small SUV (1128 kg)	57	2.4	97 (60)
Large SUV (1220 kg)	66	2.8	83 (53)
Pickup truck (1423 kg)	82	3.5	68 (45)
1050 kg - interpolated	52	2.2	105 (65)
2000 kg - extrapolated	149	6.4	37 (31)

Real-world fuel consumption of cars meeting today’s fuel consumption standards (according to current testing protocols) exceeds the national standards on average by about 25% in the US, by about 20% in Europe (based on the WLTP protocol), and by about 30% in China, while ANL has simulated adjusted (real-world) fuel consumption rates that exceed the unadjusted by about 25-30% in city driving and by 40% in highway driving. Thus, the ratio of unadjusted future ANL fuel consumption to that under the most future national standard is indicative of the further simulated reduction in fuel consumption under real-world driving conditions, except that all three regions currently give supercredits for EVs and other credits in computing average automobile fleet fuel consumption for purposes of verifying compliance with fuel consumption regulations, and this weakens the required reduction in fleet-average fuel consumption under the standards. In the absence of supercredits, the US 2025 fuel consumption standard would need to be reduced by another 40% for cars and 30% for light trucks to become comparable to that for the ANL advanced-fast mid-size car and pickup truck HEVs, respectively, while the EU and Chinese 2030 standards are already comparable to the ANL advanced-fast HEV. After accounting for dilution of standards, the improvement needed to match the ANL results would be larger in the US and potentially substantial in the EU and China.

2.3. Impact of concurrent shifts to larger LDVs

Fig. 7 shows trends in US and EU vehicle segment market shares over the period 1980–2018; since 2008, the sedan + car SUV share has fallen while the truck SUV and pickup truck shares have risen in the US, while the SUV share in the EU has risen from 8% in 2008 to 28% in 2017 (EEA, 2018). The SUVs have large frontal areas and drag coefficients.[6]

To illustrate the impact on fuel consumption of changes in the shares of different vehicle market segments, we consider three market-segment scenarios, shown in Table 4: Base, Large-Vehicle (LV), and Green. The Base scenario roughly matches the US market shares in 2010 as given by EPA (2019), while in the LV scenario, the large SUV share increases from 22% to 34% and the pickup truck share increases from 11% to 17%, with compensating changes in the mid-size car and compact-car shares. These are plausible changes, given past changes and recent trends shown in Fig. 7. The impact on average fleet fuel consumption is given in Fig. 8 for city and highway driving for fleets consisting solely of 2015 CVs, 2015 HEVs, or advanced HEVs. Fleet average fuel consumption in the Green Scenario is 9-13% less than for the LV scenario in city driving and 11–18% less in highway driving (becoming larger with more advanced technology, which disproportionately benefits smaller vehicles).

2.4. Spillover benefit for EVs of more stringent fuel consumption standards for non-electric vehicles, and implications for electricity consumption and mining

If the vehicle fleet will ultimately be converted entirely to BEVs, then the greater fuel consumption (compared to stringent across-the-board fuel efficiency standards) during the early stages of the transition will not matter in the long run. Indeed, the transition to larger vehicles also won’t matter for GHG emissions if all LDVs will be ultimately converted to C-free electricity. However, it still important to push for the greatest possible energy reductions of non-electric vehicles now, as many of the

[6] On a positive note, the market share of new vehicles with stop/start technology exceeded 70% in the EU in 2016 and reduced fuel consumption by 4-10% in city driving.

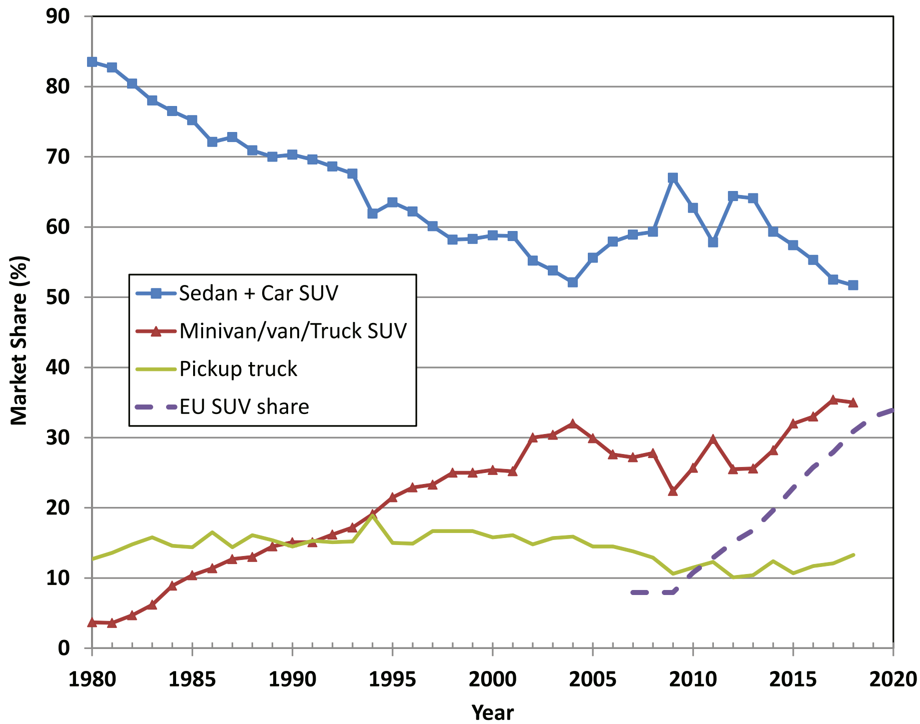

Fig. 7. Changing market segment shares in the US and SUV share in the EU. Source: US, US EPA (2019) (data for Fig 3.2, p15); EU, EEA (2018, p20).

Table 4
Alternative scenarios for shares of different vehicle market segments for new sales.

Market segment	Scenario		
	Green	Today	Large-vehicle
Compact	0.28	0.20	0.14
Mid-size	0.48	0.40	0.28
Small SUV	0.07	0.07	0.07
Large SUV	0.14	0.22	0.34
Pickup truck	0.03	0.11	0.17
Total	1.00	1.00	1.00

measures that reduce energy use in non-electric vehicles (reduced vehicle mass, reduced aerodynamic and tire resistance, reduced frontal area, and reduced auxiliary loads) will carry over to future EVs, thereby reducing the required battery and motor capacities and electricity requirements when and if the large-scale transition to EVs occurs. These "spillover" impacts on EVs are estimated in Online Supplement Section 3, and are seen to account for about ¾ of the substantial reduction in BEV electrical energy requirements (per km driven) between the 2015 and advanced BEVs. The remaining reduction in BEV energy intensity is due to measures unique to EVs that will arise with ongoing research and development.

To illustrate the benefits for electricity demand of delaying the large-scale conversion to EVs while driving deeper reductions in non-EV energy intensity, Table 5 gives the required battery storage capacity for a compact-car and pickup-truck BEVs with a 300-km range, and the required peak motor power. Required battery capacities are about 20% and 45% smaller for the advanced BEV than for the 2015 BEV under slow and fast technology development, respectively. This implies either a proportionately smaller power draw from the grid for a given charging time, or a smaller charging time if the power draw is fixed.[7]

At the same time as kWh battery capacity decreases, the required loading of Li, Co, Ni and Mn in the various Li-ion battery technologies, per kWh of storage capacity, is projected to decrease by 30-40% compared to today (see Table 3 of Harvey (2018b)). Similarly, required motor capacity (kW) could fall by up to 45% and the required loading of Nd, Dy (for permanent magnet motors) and Cu per kW of capacity could decrease by 30%. All of these metals are likely to become scarce in the future, but delay in scaling up EV production would reduce peak and cumulative mining requirements, and would also allow time to develop a capability to recycle Nd and Dy from vehicle motors. At present, there is essentially no capability for recycling of Li from vehicles or of Nd and Dy from electric motors of any kind, and recycling of Nd and Dy would be very difficult, as discussed by Bailey et al. (2017).

To illustrate the potential impact on cumulative metal demand of delaying an eventual transition to a 100% global BEV fleet, consider two scenarios for the growth in global BEV market share, dubbed BEV-Fast and BEV-Slow, and three vehicle energy intensity-BEV market share scenario combinations: frozen vehicle energy intensities combined with BEV-Fast; the ANL-Slow energy intensity scenario combined with BEV-Fast; and the ANL-Fast energy intensity scenario combined with BEV-Slow. Fig. 9 shows the two BEV market share scenarios, the cumulative mining of Li for LDVs, and cumulative oil consumption (after 2010) for LDVs for the three scenario combinations using the slow global GDP growth scenario (which drives demand for LDVs) and other assumptions as in Harvey (2018b). For these calculations, Li loading per kWh of battery capacity decreases by 30% between 2015 and 2035 while the

[7] The reduction in the required battery capacity is due in part to the efficiency measures applicable to both electric and non-electric vehicles, and to improvements in the available battery energy density (kWh/kg), which allow a reduction in EV mass above and beyond non-battery mass reductions, and in the electric drive-train efficiency, both of which further reduce the energy requirement per km driven.

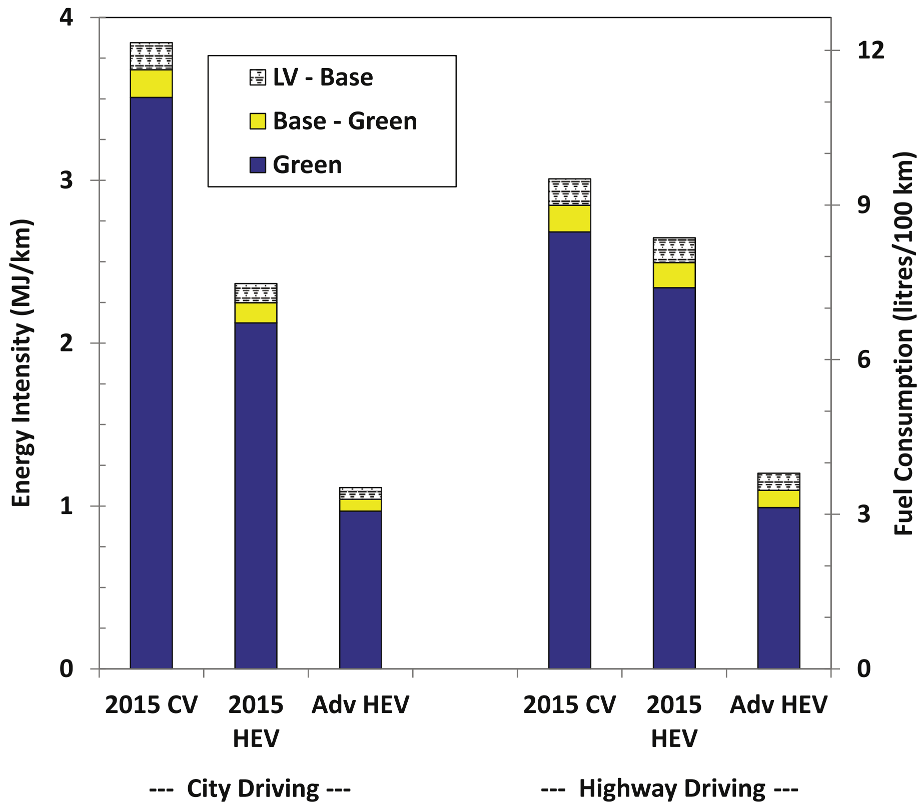

Fig. 8. Comparison of fleet average fuel consumption for the Green market shares of Table 4, and the additional assumption in going from the Green to Base and from the Base to Large-Vehicle market share scenarios. Results are shown for cases where all market segments consist of the 2015 CV, the 2015 HEV, or the Advanced HEV, for city and highway driving.

Table 5
Comparison of the battery storage capacity and peak motor power for a BEV with a 300-km range, as simulated by ANL with 2015 technology and for advanced (2050) technology under slow and fast technological progress.

	2015 BEV	Advanced BEV	
		Slow	Fast
Compact car			
Battery capacity (kWh)	75	61	41
Motor peak power (kW)	144	109	85
Pickup truck			
Battery capacity (kWh)	141	113	94
Motor peak power (kW)	262	184	144

fraction of Li from discarded batteries that is recycled increases from 1% to 70% between 2015 and 2035. The BEV share of global LDV sales reaches 30% and 70% by 2050 for BEV-Slow and BEV-Fast, respectively, and asymptotes at 100% by 2100, with the difference between BEV-Fast and BEV-Fast chosen so as to exactly offset the difference between ANL-Slow and ANL-Fast in terms of cumulative oil consumption by 2100. In spite of the identical final oil consumption, the cumulative net demand (after recycling) for Li for LDVs is significantly greater for BEV-Fast + ANL-Slow (21.7 Mt) than for BEV-Slow + ANL-Fast (14.0 Mt). Even the smaller cumulative consumption may exceed availability, as the estimated ultimately recoverable Li resource is only 7–30 Mt, which underlines the point emphasized by Harvey (2018b) that a transition to 100% BEVs in a global LDV fleet of the size typically envisaged by mid-century (2 billion or more) is unlikely to be a sustainable solution to the problem of eliminating greenhouse gas emissions from the LDV fleet.[8]

The preceding analysis assumes that a transition to a 100% BEV fleet is feasible, but that it should be delayed. It may of course not be feasible, which is another reason why governments should more strongly promote across-the-board stringent improvements in LDV fuel economy.

2.5. Safety issues

In collisions between two vehicles, safety is improved when the two vehicles have similar mass (Ross et al., 2006). Table 6 compares masses for the 2015 CV, HEV and BEV, and in 2050 as projected by ANL by under fast technological development. The 2015 compact car BEV is about 36% more massive than the 2015 CV and the 2015 pickup truck 44% more massive. In China today, BEVs are about 25% heavier than the corresponding CV (Du et al., 2018).[9] ANL projects a relatively larger decrease in BEV mass with technological development, such that advanced BEVs have slightly smaller mass than advanced HEVs. Thus, from a safety point of view, it is better to delay the large-scale uptake of BEVs until the mass difference from non-BEVs has decreased. Despite the potential for decreasing mass, vehicle mass in the EU grew by 3% from

[8] The relative difference in cumulative net Nd + Dy consumption by 2100 is much less, 1.29 Mt vs 1.04 Mt, because motor capacities are comparable for HEVs and BEVs (unlike battery capacities), and slower growth of BEV market share is partly compensated here by faster growth in HEV market share.

[9] Online Supplement Table S8 compares the mass of BEV and CV versions of various LDV models available in the US for the 2014 model year; BEV mass is only 16–28% greater than the otherwise comparable CV. Nevertheless, this is substantially greater than the HEV-CV differential, which is only 1–7% (see Table S6).

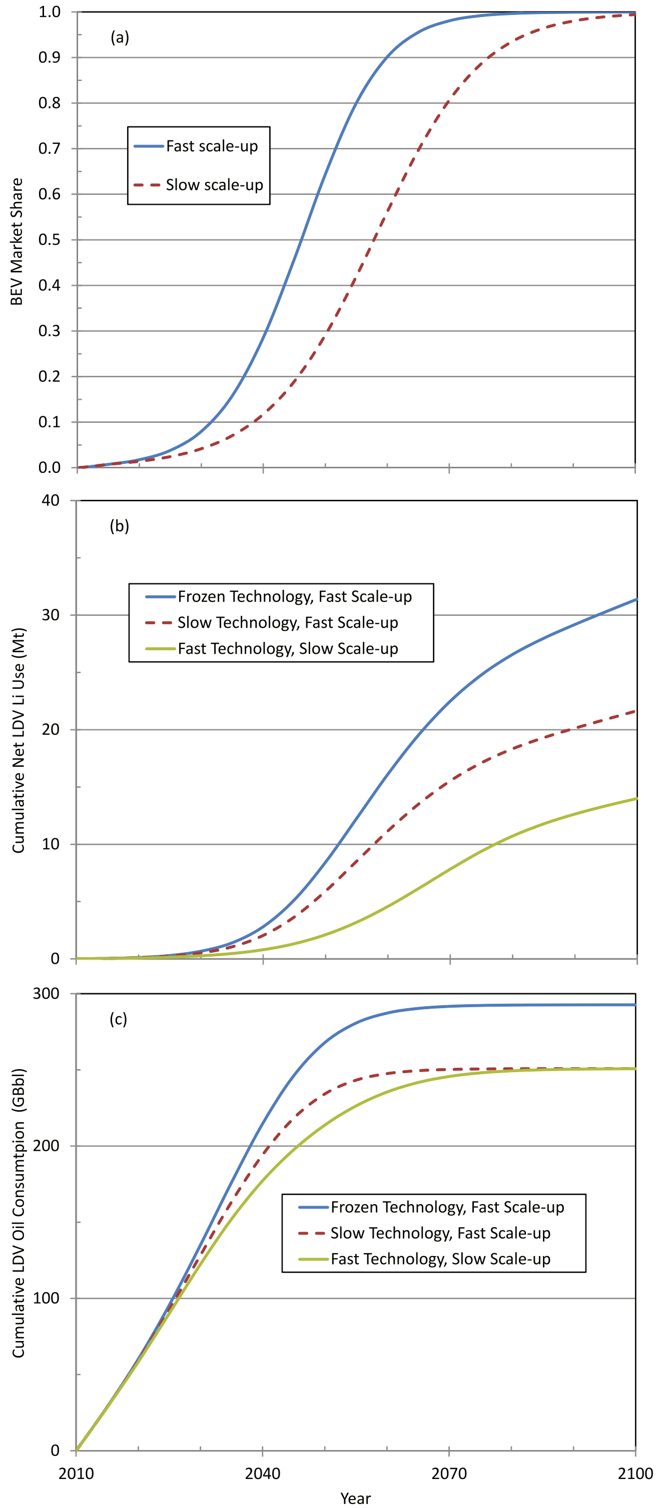

Fig. 9. (a) Scenarios for the growth in global BEV market share, and the resulting (b) cumulative net consumption of Li and (c) cumulative oil consumption related to LDVs.

2010 to 2017 (EEA (2018, p20).

3. Climate-targets context

In Paris in 2015, the nations of the world adopted the goal of "holding the increase in global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC, 2015, Article 2.1(a)). In the summer of 2018 the Intergovernmental Panel on Climate Change (IPCC) released a report detailing just how significantly worse the effects of 2.0 °C global mean warming are expected to be compared to 1.5 °C global mean warming, and showed that to have a 66% chance of limiting warming to 1.5 °C by 2100 (with a mid-century overshoot) requires that global net CO_2 emission fall to zero by 2040 (Masson-Delmotte et al., 2018, Fig. SPM.1) – a task that now appears to be impossible. The less ambitious task of limiting warming to 2.0 °C by 2100 (again, with a mid-century overshoot) requires that global net emissions drop to zero by about 2055. Simply freezing emissions at the level that would be reached in 2030 if all nations comply with the emission-reduction pledges made in Paris is estimated to entail roughly a 34% risk of warming of 3-4 °C and an 8% risk of warming greater than 4 °C (Fawcett et al., 2015, Fig. 1), with consequences that can reasonably be described as catastrophic (see, for example, Spratt and Dunlop (2019)). If "emergency" can be defined as a situation with severe consequences and very little time left to prevent these consequences, than the world is currently in a climate emergency – as recognized by resolutions passed by the British[10] and Canadian[11] parliaments and several hundred city councils across the world (CEC, 2019).

Given the emergency situation, it is essential that all measures taken to reduce greenhouse gas emissions be (i) effective, (ii) stringent, (iii) well co-ordinated, and (iv) implemented without delay. As shown here, the potential exists to reduce the energy intensity of gasoline-powered vehicles using HEVs by 55-75% in city driving and by 35-65% in highway driving compared to the 2015 CV. Furthermore, many of the changes that would be needed to get this savings in non-electric vehicles would also make EVs more efficient, reducing their impact on the electricity grid and their consumption of scarce mineral resources. Between this and improvements specifically related to EVs (namely, increased battery energy storage density and improved electric drivetrain efficiency), the electricity requirements of advanced BEVs could be reduced by about a factor of two compared to present-day BEVs.

Table 6
Vehicle masses (kg) as simulated by ANL for 2015 and for advanced vehicles (with fast technological development).

	Compact car		Light Truck	
	2015 Mass	2050 mass	2015 Mass	2050 mass
CV	1380	1068	2134	1536
HEV	1485	1095	2293	1583
BEV	1877	1069	3064	1657

4. Conclusion and policy implications

In light of the above, and acknowledging that BEVs are likely to eventually become a cost-effective and viable replacement to CVs at some scale, it is recommended here that governments.

(1) Implement eventual LDV standards comparable to those deemed to be feasible by ANL for HEVs, and that apply to the fuel use of

[10] See https://climateemergencydeclaration.org/united-kingdom-bipartisan-uk-parliament-declares-a-climate-emergency/(accessed on 25/6/2019).

[11] The Canadian resolution was passed on 17 June 2019, and reads "Canada is in a national climate emergency" requiring even deeper cuts to its greenhouse gas emissions than it has committed to making under the Paris accord. The following day, the Canadian government (i.e., the cabinet, consisting of the Prime Minister and the various Ministers) approved the construction (at taxpayers' expense) of a new bitumen pipeline so as to permit expansion in the *rate* of exploitation of one of the most C-intensive (and expensive) oil sources in the world. To be fair, I should also mention that 3 days later (21 June 2019), a new environmental assessment act was enacted which, as complained by the oil industry, makes approval of any further oil pipelines next to impossible.

vehicles, whether they be ICEVs, HEVs, or PHEVs, so as to avoid dilution of the standards.
(2) Do not allow exceptions based on vehicle mass, as these also dilute the fuel economy gains that can otherwise be achieved, but rather, formulate standards so as to encourage downsizing.
(3) Reconsider subsidy programs for EVs or at least scale down the size of the subsidies or cap the number of vehicles per year that can be subsidized, and eliminate or reduce mandatory EV sales targets.

Standards proposed for 2030 in the EU and China already exceed the ANL 2050 Fast performance results, although there is some ambiguity because the targets apply to corporate average fuel or CO_2 emission intensity after averaging in EVs with an assumed CO_2 emission of zero. Here, it is proposed that governments impose standards that regulate fuel use for vehicles when running on fuel, while working to rapidly decarbonize electricity grids and supporting research to reduce the cost, mass and material loadings of batteries and other EV components.

Automobile manufacturers that produce heavier than average vehicles will need to implement additional energy efficiency measures, change their product mix, or more heavily promote (through advertising and incentives) lower-mass vehicles. Requiring lower CO_2 emissions for LDVs with small mass acts as a *disincentive* to lower emissions by reducing vehicle mass – so these provisions need to be removed.[12]

Note that if fuel use by PHEVs when running on fuel achieves the levels simulated by ANL under fast development, this would represent a factor of 3 reduction in litres/km compared to the 2015 CV. With 60% of urban driving replaceable with grid electricity under US driving patterns (Kliesch and Langer, 2006) and 80% in Germany (Plötz et al., 2015), average fuel consumption per urban km driven would be reduced by a factor of 8-15, and moreso with a shift from SUVs and trucks toward compact and mid-size cars. Even for the ANL slow development case, the reduction would be a factor of 5-10. Rather than creating a need for an intercity network of fast recharging stations, PHEVs could be recharged solely at home or at work in a manner that minimizes grid impacts (especially with "smart" recharging, as discussed by Wang et al. (2011) and Weis et al. (2014), among others) and could provide important auxiliary services (as discussed by Pavić et al. (2015)).[13] It remains to be seen what the best approach would be for the final step to complete elimination of fossil fuels for LDVs, but whether that be a full transition to BEVs or use of biofuels or hydrogen produced from renewable energy, the transition must be accompanied by strong global measures to limit the need for automobiles in the first place (through good urban planning and public transit), as any global car-dominated transportation will eventually face resource constraints, as discussed by Harvey (2018b).

Harvey (2018a, Figs. 3–7) presented an extensive set of calculations of the net present value (NPV) of the discounted costs and savings of HEVs, PHEVs and BEVs relative to the CV, for a 6-year ownership time, a 10% discount rate and gasoline costs ranging from \$0.5–2.0/litre, based on the ANL performance and cost estimates for the 2015, 2035 and 2050 model years. For 2015 technologies and costs, and 15,000 km/yr driving, the NPV of HEVs ranges from about -\$3000 for gasoline at \$0.5/litre to about \$0 for gasoline at \$2/litre. Thus, in jurisdictions with low gasoline prices, imposing an efficiency standard for the 2015 model year that could only have been met with HEVs would have imposed an additional private cost. However, even under Slow development, the 2035 HEV is more economical than the 2035 ICEV for gasoline prices of \$1.2/litre or more (both having NPV > 0 relative to the 2015 CV, but the HEV moreso), while by 2050 the HEV is competitive with the CV for gasoline prices of \$1.0/litre or more. PHEVs and BEVs also eventually become cost competitive with CVs and also with HEVs at gasoline prices of \$1.5/litre or greater for the 2035 model year and \$1.0/litre or greater for the 2050 model year.

Consistent with these results, Supekar and Skerlos (2017) calculate that a least-cost transition to 70% lower U.S. LDV CO_2 emissions would entail shifting new vehicles sales largely from CVs to HEVs between 2018 and 2024, and from HEVs largely to PHEVs and BEVs by 2034, with complete phase-out of CVs by 2040. Although the scale-up of PHEVs and BEVs is faster than envisaged here, the important point is that a full transition of new vehicle sales to HEVs is seen as preceding scale-up of PHEVs and BEVs.

Under the normal time line to develop more efficient vehicles, 2–3 years are required for rigorous product development once the basic feasibility of a new technology has been developed, an additional 2–3 years are required for proof in production in a limited number of vehicles, and 5 years are required for roll-out across the vehicle fleet, for a total of 9-11 years (German, 2009). Both the "slow" and "fast" technology development scenarios developed by ANL were meant to be applicable to 2045 prototype vehicles and 2050 commercially-available vehicles. Given the urgency of reducing GHG emissions, this schedule could perhaps be accelerated with a coordinated international research effort and full sharing of new knowledge and technologies – creating a collaborative information commons for rapid development of efficient automobiles, similar to open-source work in genomics and informatics (Joseph, 2017, p275).[14]

Author statement

L.D. Danny Harvey: I am the sole author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

I would like to thank my former PhD student (and current Tesla owner!) Joel Krupa for insightful comments, as well as constructive comments from two anonymous reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2020.111760.

[12] Consistent with this concern, the step function mass categories in China have caused vehicle manufacturers to make sure that the vehicles they sell cluster at the low end of each category, as shown in Fig. 7 of Wang et al. (2019).

[13] Parked BEVs could also provide such services, but PHEVs could do so with greater flexibility because they don't rely solely on stored electricity, and without needing fast recharging at other times.

[14] As this paper was being finalized, the OECD (2020) released the report, "Building Back Better: A Sustainable, Resilient Recovery after COVID-19". Paragraph 26 reads "The automotive sector is a major global employer … and has been severely affected by the COVID-19 crisis. As governments consider longer-term support for ailing manufacturers, they can ensure that such support is contingent on environmental improvements including accelerating the shift to electric cars *as well as more efficient, cleaner ICE vehicles* [emphasis added]. However, recovery measures should also embrace a shift towards mobility systems designed around accessibility … rather than emphasizing an accelerated uptake of private electric vehicles … A mobility system based heavily on private vehicles is also badly equipped to achieve other social and economic goals (e.g. reduced inequality, better health and less congestion)". Thus, the OECD cautions against support for private automobiles to the exclusion of other forms of mobility, and cautions against support for electric vehicles to the exclusion of more efficient ICE vehicles, thus reinforcing the recommendations made here.

Funding

This research received no funding support in the public, commercial, or not-for-profit sectors.

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