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Are vehicle lifespan caps an effective and efficient method for reducing US light-duty vehicle fleet GHG emissions?

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Abstract

With light duty vehicles (LDVs) responsible for 17% of annual US greenhouse gas (GHG) emissions, integrating emerging GHG-reducing technologies into the fleet is essential. However, the slow rate of vehicle turnover presents a significant barrier to the market penetration of new technologies, with adoption delayed by the low number of vehicles needing replacement each year. A strategy of accelerated vehicle turnover through a vehicle lifespan cap could potentially mitigate this limit. While older studies reach differing conclusions on their effectiveness, two newer studies that incorporate life cycle assessment find that accelerated turnover strategies can be effective if coupled with high levels of electric vehicle deployment. We seek to determine whether a vehicle lifespan cap strategy can be an effective and efficient (cost-effective) method for reducing US LDV fleet GHG emissions. We augment the capabilities of the Fleet Life Cycle Assessment and Material Flow Estimation (FLAME) fleet life cycle assessment model, integrating vehicle lifespan caps and comprehensive calculations of cost along with sensitivity analysis for electric vehicle survival curves and battery degradation. The augmented FLAME model is used to analyse the impact of vehicle lifespan caps of varying lengths on a suite of scenarios, including a business as usual (BAU) scenario and eight scenarios modelling different technology improvement assumptions. This work confirms that vehicle lifespan caps have limited effectiveness in reducing GHG emissions under a BAU scenario but show potential to meaningfully reduce GHG emissions in a scenario with accelerated deployment of electric vehicles. However, abatement costs are high, exceeding 2020 USD 1000/tCO_2eq under baseline assumptions, but falling within the range of current estimates of the social cost of carbon under more optimistic assumptions. Overall, vehicle lifespan caps must be carefully considered as they accelerate both the benefits and costs of new vehicle technologies, and are best positioned as part of a larger integrated strategy for tackling transportation GHG emissions.

1. Introduction

Light duty vehicles (LDVs) are responsible for 17% of total US greenhouse gas (GHG) emissions [1]. As such, rapidly reducing emissions from LDVs is a crucial component of a comprehensive response to the accelerating climate crisis. Emerging technologies hold the promise of dramatically reducing the GHG emissions associated with LDVs, including technologies leading to vehicle lightweighting, improvements in fuel efficiency, and the deployment of electric vehicles. But with the average lifespan of an LDV in the US a little over 15 years [2], the ability for these new GHG-reducing technologies to penetrate the market remains limited. The slow rate of LDV fleet turnover restricts the rate at which new technologies can be deployed on the road.

The strategy of accelerating fleet turnover through a vehicle lifespan cap is designed to directly mitigate the impact of slow fleet turnover, getting new technologies on the road faster. However, a vehicle lifespan cap strategy comes with counterbalancing negative impacts that must be considered. Therefore, a central question in the study of vehicle lifespan caps is whether they are a viable and desirable strategy for reducing the GHG emissions of the US LDV fleet?

Previous research into accelerated vehicle turnover has produced mixed outcomes, with studies coming to different conclusions on the level of effectiveness and costs of vehicle turnover policies. More recent research that includes life cycle assessment (LCA) has concluded that early vehicle retirement is useful for accelerating EV market penetration [3, 4]. Taken as a whole, the body of research on vehicle lifespan caps is limited, having not simultaneously incorporated salient factors and inputs including fleet dynamics, recent technology forecasts, and the diversity of technological assumptions that may influence both GHG emissions and associated costs.

Directly addressing the question of the financial viability and desirability of vehicle lifespan caps, this work seeks to determine whether such caps are an effective and efficient (cost-effective) method for reducing US LDV fleet GHG emissions. This work builds on previous assessments of vehicle turnover strategies by expanding the capabilities of the Fleet Life Cycle Assessment and Material Flow Estimation (FLAME) model, developed in our prior work [5, 6]. Along with adding the ability to model vehicle lifespan caps to the FLAME platform, this work incorporates comprehensive calculations of cost along with other important factors including electric vehicle survival curves and battery degradation.

In this paper we first examine the context for this work, looking at both the potential and pitfalls of vehicle lifespan caps in reducing GHG emissions from LDVs. The existing body of research on accelerated fleet turnover strategies is reviewed, and the specific focus of this work is examined within the context of this literature. The methods used in this work are detailed, and the results of our analysis are presented. We then discuss the implications of these results, review the limits of this study, and examine other considerations and future work before concluding with a summary of our findings and their implications for the future role of vehicle lifespan caps in reducing GHG emissions in the US LDV fleet.

2. Context—accelerated fleet turnover for GHG reduction

Climate action in all sectors is required to meet global goals and to avoid the most critical climate change repercussions [7]. Reductions in GHG emissions must not only be deep, but also rapid to avoid exhausting allowable carbon budgets or inducing irreversible climate-related adverse impacts and damages [8]. Transportation emissions accounted for 29% of total US GHG emissions; of this the largest portion (58%) resulted from LDVs (passenger cars and trucks) [1]. Reducing GHG emissions from the LDV fleet is critical to mitigating climate change.

Strategies for reducing LDV GHG emissions are typically categorized into the avoid, shift, and improve hierarchy [9, 10]. 'Avoid' means prioritizing reducing vehicle kilometres travelled (VKT). 'Shift' aims to encourage non-motorized or less carbon intensive travel modes. 'Improve' includes technological improvements to personal vehicles or fuels. Strategies that fall under the umbrella of technological improvements include: improving vehicle fuel efficiency, vehicle lightweighting, moving towards smaller vehicles, and deploying alternative fuels and vehicles that have a lower life cycle carbon intensity [3, 6, 11–15]. Alternative fuels include various low-carbon renewable fuels, and alternative vehicles include battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), among others [16–20].

There is a general consensus that many of these new and emerging technologies have the potential to substantially reduce per-vehicle GHG emissions. However, when examining the potential impact of new vehicles with reduced GHG emissions a major limiting factor becomes evident. Even under scenarios where new vehicles sold feature highly effective GHG reducing technologies, the time required for fleet turnover keeps inefficient vehicles on the road while delaying alternative vehicle penetration, limiting the impact that technological improvement can have over short and medium time scales [4, 5, 21, 22]. Prior authors have noted the limiting role of fleet stock turnover in deep decarbonization of the US fleet and have proposed policies that target vehicle fleet turnover as a method of accelerating the transition to an efficient and adaptable fleet [22, 23].

Accelerating fleet turnover, through incentivized or mandated scrapping of older vehicles, increases the GHG reduction potential of technological improvement strategies during the operation phases of the vehicles' lifecycles. This occurs as scrapped vehicles are replaced with newer more efficient models, reducing overall fleet fuel use, and amplifying the effects of lower emissions vehicle deployment and vehicle lightweighting [24–28].

Counterbalancing the GHG reduction potential of an accelerated fleet turnover strategy are several negative impacts including (1) increases in production and end-of-life emissions due to the higher number of vehicles that are manufactured and scrapped, and (2) increased costs due to more frequent vehicle purchases [27]. These impacts are magnified when looking at EVs as compared to conventional internal combustion engine (ICE) vehicles due to the higher embodied emissions associated with battery production and currently high battery costs [29, 30].

3. Background and literature review

Previous work on accelerated fleet turnover typically focused on one of two areas: (1) projecting the impact of higher vehicle turnover rates on future GHG emissions [21, 27, 31, 32], or (2) assessing the impact of historic scrappage programs [33–41].

3.1. Projecting the impact of higher vehicle turnover rates on future GHG emissions

Singh *et al* [32] found that projected accelerated scrappage policies for the Indian vehicle fleet would have a low impact on fleet emissions and attributed this to the low share of old vehicles in the fleet, and their respective low share of kilometres travelled. In contrast, Nakamoto and Kagawa [31] considered product lifetimes modelling for LDV and found that decreased lifespans could actually increase GHG emissions in Japan, as the emissions reduced during vehicle use were not enough to compensate for increased production phase emissions.

Kim *et al* [27] found the optimal vehicle replacement interval was 18 years for reducing GHG emissions, when considering a generic mid-size US passenger vehicle during the period 1985–2020. A 2005 expansion of Kim *et al*'s work by Spitzley *et al* [21] found that longer vehicle lifespans kept total ownership costs down, while shorter vehicle lifespans reduced CO and NO_X emissions. The studies [21, 27, 31], did not consider the dynamics of a vehicle fleet, including the change in kilometres travelled with vehicle age, and did not include vehicles with different powertrains. They [21, 27, 31, 32] also did not capture more recent trends in fuel economy and vehicle powertrains, such as the rise in EV adoption.

More recent work by Zhu *et al* [3] and Naumov *et al* [4] used LCA based US vehicle fleet models and found early vehicle retirement to be a useful component for accelerating EV market shares. Zhu *et al* [3] found that vehicle lifespan caps can increase the likelihood of meeting US climate targets when combined with high EV deployment, but unlike the current study did not consider cost-effectiveness or examine factors that could negate the effects of early vehicle retirement. Naumov *et al* [4] utilized consumer choice modelling to investigate the effectiveness of different levels of incentives for accelerating LDV fleet turnover [4]. Naumov *et al*'s work identified an abatement cost of around \$600 to \$1200 per tonne for cumulative CO_2 emissions reductions of 0.3%–0.5% by 2050 when using \$4000 and \$8000 incentives for early vehicle retirement and replacement with an EV or highly efficient ICE vehicle (ICEV). Modelled reductions increased to 2% and abatement costs dropped to \$124 per tonne CO_2 when replacement was restricted to only EVs, primarily due to associated market feedbacks driving down the cost of EVs.

3.2. Assessing the impact of historic scrappage programs

Policies that increase vehicle turnover and keep younger vehicles on the road include 'cash for clunker' type programs and Singapore's vehicle quota, which, due to the high cost of extending vehicle ownership beyond 10 years, effectively caps vehicle lifespans at 10 years with few vehicles being kept to 15 years [42–45]. These types of policies have been implemented to reduce air pollution, improve energy security, and boost new car sales.

Analyses of the vehicle scrappage programs that have been run in Japan, Germany, and the US have found that they delivered reductions in GHG emissions from their respective vehicle fleets, but typically faced high costs for the small scale of reductions achieved [33–38]. Analysis of the Italian car scrappage scheme by Marin and Zoboli [39] found that high incentives were necessary to motivate participation, while Lueth *et al* [37] indicated that in the UK, car sales were not boosted as owners were resistant to early scrappage. The Singapore vehicle quota limited annual car population growth from a previous rate of 5.8% annually to 3.6% annually but has seen a growth in per VKT [42, 43].

3.3. Literature review findings

Previous studies have produced mixed outcomes, showing differing perspectives on the level of effectiveness and costs of vehicle turnover policies, depending on background vehicle fleet characteristics and modelling choices. However, recent studies show benefits for introducing vehicle fleet turnover policies as a method of increasing EV penetration in the fleet [3, 4]. We are not aware of work that projects changes in the fleet's total ownership costs following policies that accelerate vehicle fleet turnover with the aim of promoting EV adoption.

Despite some past work examining early vehicle retirement the body of literature is limited, especially with respect to fleet dynamics, recent technology forecasts, and the diversity of technological assumptions that may influence both the associated GHG emissions and costs. In this paper, we augment our established US vehicle fleet LCA model—FLAME [5, 6] with new capabilities to simulate costs and GHG emissions associated with early vehicle retirement. FLAME has previously been used to assess impacts of vehicle lightweighting [6], the role of EVs in meeting climate targets [5] and associated battery material demands [46], and the mitigation potential of improvements to gasoline vehicles [47], among others. The modelling framework has since been adapted for use in other countries, including Canada [48], China [49], and the UK [50]. Notably, however, FLAME did not previously have the capability to simulate early vehicle retirement, despite its prior results showing fleet turnover to be a key barrier for new technologies (i.e. EVs) to assist in meeting climate targets. The enhanced capabilities within FLAME realized in this research allow for a deeper exploration of the potential GHG mitigation role of early vehicle retirement within a fleet LCA framework.

4. Research focus

This work seeks to determine whether vehicle lifespan caps are an effective and efficient (cost-effective) method for reducing US LDV fleet GHG emissions. This research objective translates directly into the two research questions being answered in this work:

(1) under what set of conditions would vehicle lifespan caps <u>be effective</u> at reducing GHG emissions from LDVs, and;
(2) would vehicle lifespan caps be a <u>cost-effective</u> mechanism for reducing GHG emissions from LDVs.

For the purposes of this work the term 'effectiveness' is defined as the abatement potential, determined by comparing the mass of GHG emissions reduced to a business as usual (BAU) baseline. The term 'cost-effectiveness' is defined as the estimated abatement cost of GHG emission reductions, measured as USD per tonne of GHG emissions reduced.

The thirty-year period spanning 2020–2050 was chosen as the window of study for this work to illustrate emissions and costs associated with the dynamics of fleet turnover on a time-scale relevant to global climate targets.

4.1. The unique contribution of this research

Distinct from previous assessments of vehicle turnover strategies, this work focuses on a wide range of strategies combined with accelerated fleet turnover, includes fleet ageing characteristics, identifies conditions required for vehicle turnover to be effective (such as the rate and timing of strategy implementation) and estimates total costs. Its implementation within FLAME provides new capabilities to an established fleet LCA model, and serves as important confirmation (and extension) to prior results in the emerging field of fleet LCA.

5. Methods

5.1. Overview

In this paper we model the US LDV fleet from 2020 to 2050 under nine scenarios and use a variety of assumptions. The nine scenarios include a BAU scenario and eight scenarios that incorporate a variety of vehicle technology improvements that reduce GHG emissions, as described below.

We first estimate fleet level GHG emissions for our nine scenarios using a variety of assumptions regarding the rate and timing of lifespan cap implementation. We then estimate the fleet level costs for these scenarios and assumptions, including estimates of material use, fleet level costs, and abatement costs for each scenario. Single vehicle replacement analysis complements the fleet level modelling by quantifying GHG emissions and cost implications for individual drivers.

In this section we detail the research methodology outlined above. We first review the nine scenarios used in our modelling, and then describe both the FLAME model at the heart of this study and the augmentations implemented in this work. The methods for calculating fleet level emissions, fleet level costs, and GHG emission abatement costs are presented, and this overview of research methods concludes with a brief discussion of the single vehicle replacement analysis that is conducted as a complement to the fleet level analysis.

5.2. Modelling nine scenarios

This study models the US LDV fleet using nine defined scenarios: a BAU scenario and eight scenarios that model various technology improvements that reduce vehicle GHG emissions. The BAU scenario, which sees no lifespan cap implemented, establishes the baseline used throughout this analysis.

Beyond the BAU scenario, six technological improvement options are considered to further understand the role of lifespan caps as an accelerant for fleet improvements. The scenarios include reductions in vehicle size, reductions in vehicle weight, reductions in vehicle fuel consumption, HEV deployment, PHEV deployment, and BEV deployment. Vehicle size reduction adjusts projected vehicle stock to reflect a change in the light truck market shares to historic data (lower proportion) rather than more recent data (larger share). Vehicle weight reductions are based on aluminium maximum light-weighting previously studied by Milovanoff *et al* [6]. The high fuel efficiency improvement scenario is based on high fuel consumption improvements previously developed by Milovanoff *et al*, which improves ICEV-G (gasoline) car fuel efficiency from about 8.04 l/100 km in 2020 to 6.88 l/100 km in 2050 and BEV300 car fuel efficiency from about 21.3 kWh/100 km in 2020 to 18.4 kWh/100 km in 2050 [6]. The HEV, PHEV, and BEV deployment scenarios each follow an increase of HEV, PHEV, or BEV sales from 2020 to 2035 to reach 100% of new sales by 2035 based on recent policy targets for 100% of new sales as zero emission vehicles for the same year [51].

Two combination scenarios integrate the above technological improvements. The high technological improvement scenario includes reductions in vehicle size, vehicle weight, and vehicle fuel consumption (above and beyond those achieved by vehicle weight reductions). The high technological improvement and EV deployment scenario includes reductions in vehicle size, vehicle weight, and vehicle fuel consumption, along with 100% of new sales as BEVs by 2035.

As will be seen in the results, only those scenarios with rapid BEV penetration show meaningful mitigation potential associated with vehicle lifespan caps. Thus, after presenting baseline results for all scenarios, the remainder of the paper will focus on the BAU scenario (i.e. to provide a baseline) and the BEV deployment scenario (i.e. the main scenario in which lifespan caps are potentially worth considering).

Table 1 provides an overview of the nine scenarios.

5.3. The FLAME model

The model used for scenario analysis is adapted from the FLAME model [5, 6]. FLAME is a fleet model, developed and applied by Milovanoff *et al* [5, 6] to quantify the maximum GHG reductions that may be achieved in the US LDV fleet by 2050 through vehicle light-weighting with aluminium and through high levels of fleet electrification, based on historic vehicle turnover and projected sales.

The FLAME model combines vehicle fleet modelling with LCA methods. Vehicle fleet models track and project vehicle stocks by type and age, in a fleet, and project the composition of the fleet in future years. LCA considers all life cycle stages during a vehicle lifetime to assess the environmental impact of manufacturing, driving, and scrapping a vehicle. Combining LCA methods and vehicle fleet modelling allows assessment of how quickly technologies reducing GHG emissions can penetrate the fleet, building in temporal changes in background systems (e.g. the electric grid) and ensuring environmental trade-offs for all life cycle stages are considered [53, 54]. FLAME also outputs projections of fleet kilometres travelled and fleet level material use, which can complement LCA outputs.

FLAME consists of four modules that together calculate the annual life cycle GHG emissions of the US LDV fleet [6]. These modules are the vehicle module, fleet module, automotive material flow module, and LCA module (figure 1) [6]. The vehicle module projects vehicle characteristics by type and includes projected fuel consumption improvements and light-weighting. The fleet module projects annual fleet stock as well as annual fleet VKT and fuel use. The automotive material flow module assesses primary material demands for the projected fleet, as well as the quantity of materials available from scrapped vehicles for recycling. The types of materials covered focus on the vehicle body, specifically aluminium and steel. The LCA module connects the demands from the fleet and material flow modules to GHG emissions factors. Outputs from FLAME include the projected VKT, vehicle stock, fleet level material consumption, and fleet level GHG emissions (CO_2, CH_4, N_2O), which we aggregate using 100 year global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report [55]. These values are 1, 28, and 265 CO_2e for each of CO_2, CH_4, and N_2O, and are still pertinent since the release of the 6th Assessment Report as the majority of modelled emissions are CO_2 and the GWP values have not changed substantially from the 5th to the 6th report.

This study adds three additional modules to the core FLAME platform. These modules use the outputs of the four core FLAME modules to calculate associated costs, with a module for each of vehicle cost, fuel cost, and use phase cost. The methodology employed in each of these three modules is detailed further on in this section—see the section 5.7 *Calculating Fleet Level Costs Per Scenario*.

Figure 1 provides an overview of the modules deployed in our augmented FLAME model.

Table 1. Main scenarios for assessing effectiveness of vehicle turnover policies in reducing US light-duty vehicle fleet GHG emissions from 2020 to 2050.

Scenario	Vehicle powertrain projection	Vehicle size projection	Fuel consumption improvement	Vehicle lightweighting
Business-as-usual (BAU)	Market shares for vehicle powertrain follow AEO 2021 [52] projections.	Market shares for vehicle size follow AEO 2021 [52] projections.	Low fuel efficiency improvements	No lightweighting
Reduction in light trucks	Same as BAU	The sales market share of light trucks decreases by 0.5% annually to match historic proportion.	Same as BAU	Same as BAU
Vehicle lightweighting	Same as BAU	Same as BAU	Same as BAU, with additional reductions from lightweighting	Aluminium maximum lightweighting developed by Milovanoff *et al* [6].
High fuel efficiency improvement	Same as BAU	Same as BAU	High fuel efficiency improvements developed by Milovanoff *et al* that improve ICEV-G car fuel efficiency from 8.04 l/100 km in 2020 to 6.88 l/100 km in 2050 and BEV300 car from 21.3 kWh/100 km in 2020 to 18.4 kWh/100 km in 2050 [6]	Same as BAU
HEV deployment	Market share for vehicle powertrain type is adjusted to linearly increase electric vehicle sales to reach 100% of new sales as HEV by 2035.	Same as BAU	Same as BAU	Same as BAU
PHEV deployment	Market share for vehicle powertrain type is adjusted to linearly increase electric vehicle sales to reach 100% of new sales as PHEV40 by 2035.	Same as BAU	Same as BAU	Same as BAU
BEV deployment	Market share for vehicle powertrain type is adjusted to linearly increase electric vehicle sales to reach 100% of new sales as BEV300 by 2035.	Same as BAU	Same as BAU	Same as BAU
High technological improvement	Same as BAU	The sales market share of light trucks decreases by 0.5% annually.	High fuel efficiency improvements, with additional reductions from lightweighting	Aluminium maximum lightweighting developed by Milovanoff *et al* [6].
High technological improvement and EV deployment	Market share for vehicle powertrain type is adjusted to linearly increase electric vehicle sales to reach 100% of new sales as BEV300 by 2035.			

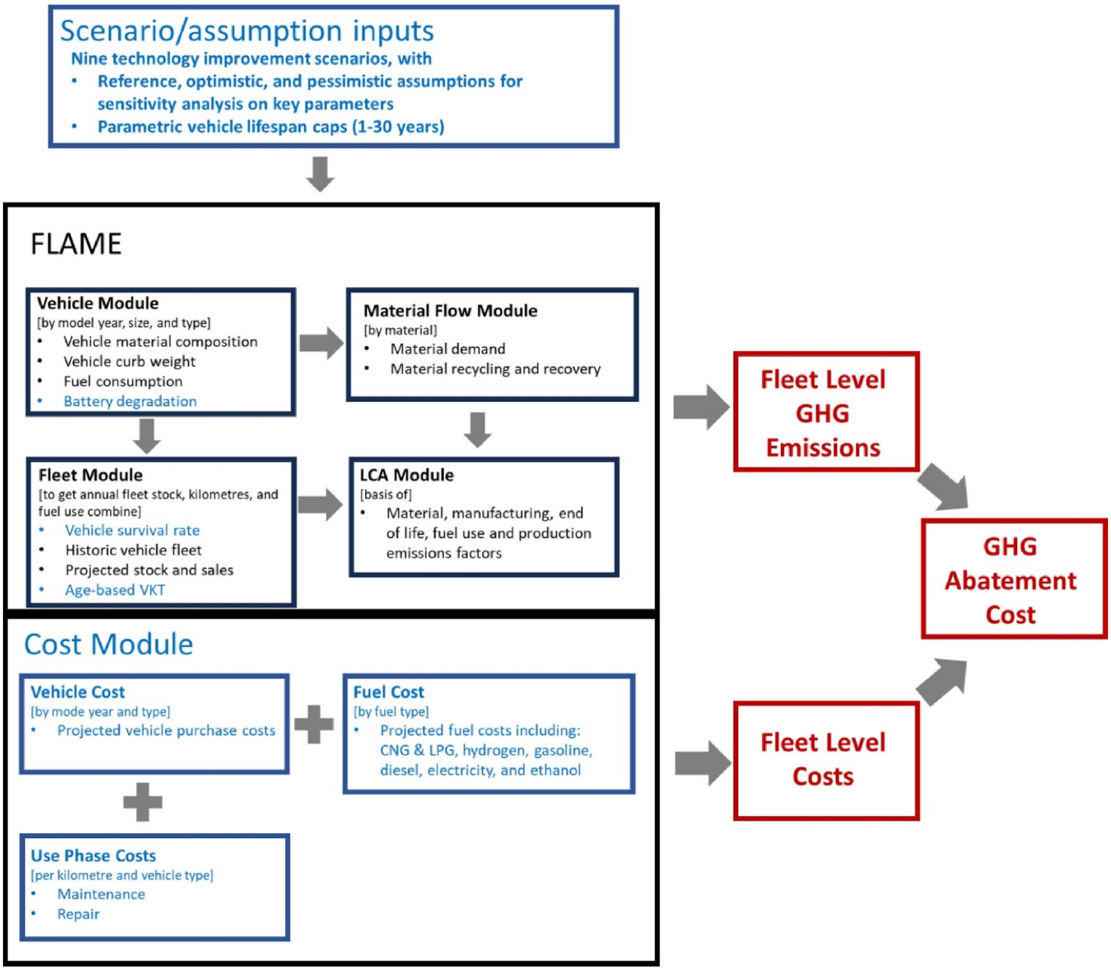

Figure 1. The methods used to calculate the fleet level GHG emissions and fleet level costs for the US LDV fleet from 2020 to 2050 combine a modified version of the Fleet Life cycle Assessment and Material flow Estimation (FLAME) model [5, 6] with modules for total ownership costing. Text in black provides an overview of the existing FLAME model. Text in blue indicates new inputs and model enhancements developed in this work. Text in red indicates results metrics. Adapted with permission from [6]. Copyright (2019) American Chemical Society. Adapted from [5], with permission from Springer Nature.

Within FLAME, vehicles are categorized by their size, powertrain type, and age. Vehicle sizes are categorized as cars and light trucks, following the Energy Information Administration (EIA) vehicle size categories [52]. Powertrain types include conventional internal combustion vehicles (ICEV-G (gasoline) and ICEV-D (diesel)), battery electric vehicles (BEV100 and BEV300), plug-in hybrid electric vehicles (PHEV20 and PHEV40) and other alternative vehicles (FCV—fuel cell vehicle, FFV—flex fuel vehicle, HEV—hybrid electric vehicle, CNG—compressed natural gas internal combustion vehicle). Vehicle survival is determined based on Transportation Energy Data Book (TEDB) survival rate curves (age based), and per VKT are based on historic VKT data, which differ by vehicle age [2].

The Supplementary Material gives an overview of underlying data from FLAME most relevant when considering vehicle turnover, such as vehicle survival rates and VKT, while further details on the model are provided in Milovanoff *et al* [5, 6].

5.4. Augmenting the FLAME model

In addition to the costing modules described above, this work augments the underlying FLAME model with three important additions: vehicle lifespan caps, electric vehicle specific survival curves, and electric vehicle battery efficiency degradation.

5.4.1. Implementing vehicle lifespan caps

Vehicle lifespan caps are added by changing the vehicle survival rate within FLAME, which is based on the TEDB [2]. When a lifespan cap is implemented the survival rate after that year goes to zero, meaning that no vehicles survive past the lifespan cap year. The vehicles are assumed to be scrapped at that time. In the years leading up to the lifespan cap, vehicle survival rates are still determined by the empirical historical survival

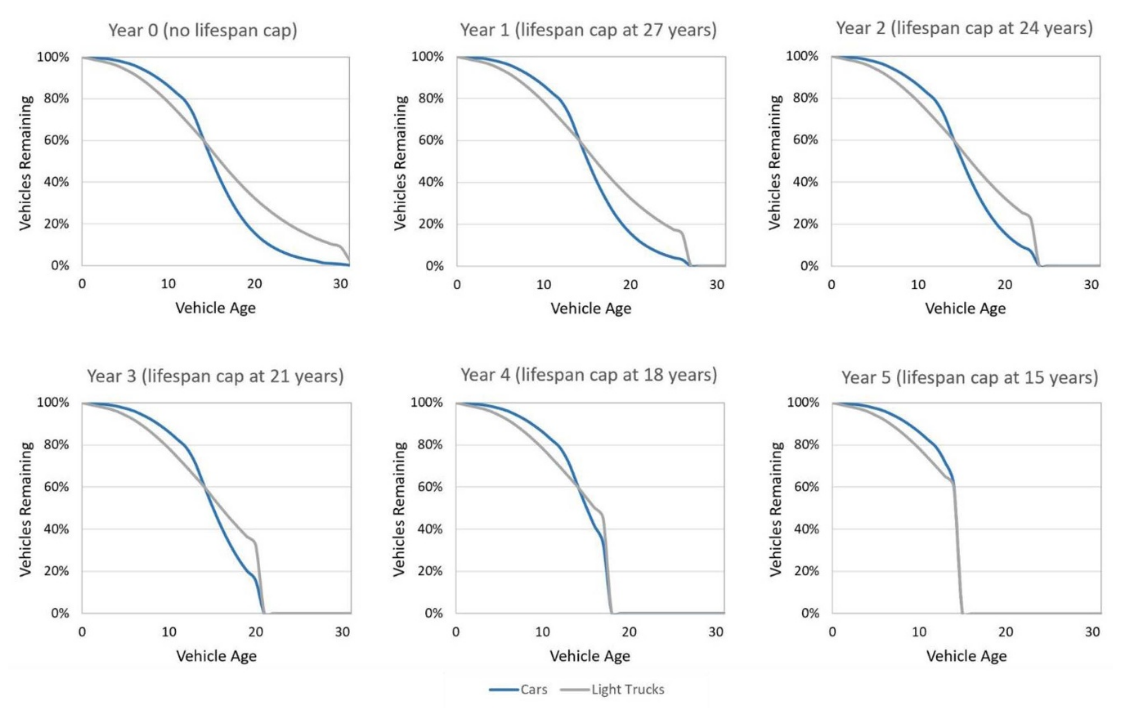

Figure 2. Survival rate implementation that shows the percentage of vehicles remaining of a model year as the vehicles age, or cumulative survival of a vehicle model year. The figure shows an illustrative implementation with a 5-year transition period toward a 15-year lifespan cap. The first panel shows empirical data from the Transportation Energy Data Book [2], labelled as year 0 (i.e. before any cap is introduced). Subsequent panels introduce an increasingly stringent lifespan cap in annual increments until the reaching the 15 year (illustrative) cap, which remains in effect for the duration of the model run.

rate curve. In FLAME a 30 year lifespan cap is equivalent to no lifespan cap being implemented, and vehicle lifespan caps of 1–30 years were considered in this research. Figure 2 gives a visual representation of what happens to vehicle survival when an illustrative 15 year lifespan cap is implemented using a five-year transition period.

During lifespan cap implementation, the steep onset of a lifespan cap causes spikes in vehicle sales to compensate for the sudden scrapping of a large number of vehicles. To avoid this unrealistic spike in vehicle production and scrappage a transition period can be introduced during which the lifespan cap age is decreased linearly until the target lifespan cap is reached. Such a transition serves to delay the onset of the vehicle lifespan cap, controls the rate of lifespan cap implementation, reduces spikes, and allows automakers more time to adjust to the new turnover. This paper presents the results of scenarios run with a five-year transition period built into the vehicle lifespan cap implementation. The results for scenarios run with (A) no transition period and (B) a ten-year transition period are presented in the supplementary material (S2.1.2 and S2.2.2).

FLAME projects US vehicle stocks by combining the projected number of vehicles with the market share of projected sales. Both the projected stock numbers and the market share percentages of sales are based on 2021 Annual Energy Outlook (AEO) projections [52]. In this way, annual sales numbers are determined based on the number of vehicles needed to meet stock projections, while the vehicle types sold are determined based on projected sales market shares of vehicle size and powertrain type for that year. When a vehicle lifespan cap is implemented, the total number of vehicles on the road stays the same, as new sales are assumed to make up for higher vehicle scrappage rates. This assumption enables us to focus specifically on the technological implications of the scrappage policy, but may underestimate potential GHG benefits from reduced vehicle ownership due to some vehicles that are scrapped not being replaced.

The VKT function in FLAME has likewise been adapted to account for the decreasing average fleet age under the simulated lifespan cap policies. In FLAME, total fleet kilometres travelled is the product of VKT and the number of vehicles. The per vehicle annual kilometres have an age-based distribution, with new cars being driven about 14 000 km in their first year, gradually declining to about 5000 km by age 30, consistent with empirical observations [2]. Trucks are driven slightly more than cars, starting at about 16 000 km in their first year, gradually declining to about 6000 km at age 30, also based on empirical data [2]. This results in FLAME projections estimating an increase in total fleet kilometres travelled under high lifespan caps as the proportion of new cars increases. A new adjustment procedure has been implemented that scales the total fleet kilometres so that under all lifespan cap scenarios the total fleet kilometres are the same as under a no lifespan cap scenario. This assumes no increase in VKT from people owning newer vehicles. However, an increase in fleet kilometres travelled due to more new vehicles being on the road may actually occur as replacement vehicles would have lower average fuel consumption and may be more comfortable or reliable [26]. Because it is difficult to ascertain whether this behavioural change would occur, an additional attribute has been implemented that parametrically assesses how much of an impact increased kilometres travelled due to newer vehicles on the road can have. Here 100% rebound represents all new vehicles being driven at the rate of a new vehicle (the fleet kilometres are determined based on the empirical distribution of VKT across vehicle ages), while 0% represents a downward adjustment to keep fleet kilometres travelled equal across scenarios. Details are included in the supplementary material section S1.1.2.2.

We have embedded two options for lifespan caps in FLAME: (1) technology specific caps, and (2) universally applied caps. When the technology specific option is used the lifespan cap only applies to conventional vehicles (ICEV-G and ICEV-D), while EVs follow the unmodified historic survival curve. When the universal option is used the lifespan cap is applied to all vehicle types.

Our implementation of lifespan caps also includes the ability to set the year in which vehicle lifespan caps come into effect. The scenarios used in our analysis had the start of lifespan cap implementation set for 2020. Additional scenarios with lifespan cap implementation starting in 2025 and 2035 are included in the supplementary material section S2.2.3.

5.4.2. Electric vehicle survival curves

Studies by Thorne *et al* and Yu *et al* suggest that electric vehicles may not follow historic vehicle survival curves and have the potential to be scrapped earlier than conventional vehicles [56, 57]. Previous work with FLAME did not consider these reduced survival rates of electric vehicles. For this work, reduced survival rates for EVs are built into the 'pessimistic' set of assumptions used in sensitivity analyses, using the survival rate curves for EVs developed by Thorne *et al* [56]. Thorne *et al*'s EV survival curves are based on early EV deployment data, using about 6 years of empirical scrapping data on EVs, and projecting forwards using ICEV retirement rates [56]. See the supplementary material section S1.1.2.1 for more details.

5.4.3. Battery degradation

Previous versions of FLAME did not account for vehicle ageing impacts, which may influence the effectiveness of vehicle lifespan caps. To include this impact, vehicle ageing factors are added to FLAME. Prior authors found that vehicle efficiency degradation with age is insignificant for conventional vehicles [58, 59]. However, EVs face battery degradation with age, which can increase vehicle energy consumption [60–66]. Electric vehicle battery degradation remains highly uncertain due to little on road vehicle data, and the relatively short window (10–14 years) for the few studies that have collected efficiency data. Yang *et al* [61] found up to a 28% increase in fuel consumption after 10 years of driving EVs. This result is implemented in FLAME as an upper bound sensitivity assumption, where EV fuel consumption increases about 4% annually. Lower bound and reference assumptions in FLAME implement no battery efficiency degradation as it is expected that battery and battery management technology will continue to improve [67, 68].

5.5. Calculating fleet level GHG emissions per scenario

5.5.1. The BAU scenario

The BAU scenario, which sees no lifespan cap implemented, provides the baseline data used to calculate GHG emissions. The EIA's 2021 AEO [52] vehicle stock projections are used to determine the number of vehicles that will be on the road as well as the annual market sales share by type from 2020 to 2050. The VKT are then determined by combining the number of vehicles with the figures for per VKT provided in the TEDB [2]. Vehicle material composition and recycling rates are based on historic US data previously consolidated into a BAU scenario by Milovanoff *et al* [6]. Vehicle fuel consumption is based on low fuel consumption improvement projections that would have been consistent with the SAFE standards. The SAFE fuel consumption improvements are used as they represent a conservative scenario, despite the return to CAFE standards [69]. GHG emissions intensities for vehicle production and fuel production are based on Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies 2017 Model as described in [6]. Electricity grid GHG intensity follows 2021 AEO Reference Case projections of the annual US grid mix, combined with life cycle GHG intensity factors for electricity production of each generation type in the US from Ecoinvent as described in[6].

5.5.2. Technology improvement scenarios

In all technology improvement scenarios, lifespan caps are assessed parametrically from 1 to 30 years, under both the technology specific and universal lifespan caps. When a lifespan cap is applied, scrapped vehicles are replaced with new vehicles in proportion to their projected sales market share, differentiated by vehicle size and powertrain type. Total fleet kilometres travelled and total fleet size are kept equivalent to the BAU scenario with no lifespan cap.

5.6. Analysis of the sensitivity of GHG emission reductions to various contributing factors

Additional sensitivity analysis is conducted on two of the nine scenarios studied: the BAU scenario and the BEV deployment scenario. These two scenarios were chosen as BAU provides a baseline (and also a lower bound on the effectiveness of lifespan caps), while BEV deployment illustrates the main scenario in which lifespan caps are potentially effective. The sensitivity analysis looks at the sensitivity of GHG emissions results to various model input parameters, with a focus on parameters relevant to the BEV deployment scenario as this scenario showed the greatest potential effectiveness for vehicle lifespan caps.

For both the BAU and BEV deployment scenarios we examine the sensitivity of GHG emissions to potential changes in electricity grid GHG intensity, fleet kilometres travelled, VKT rebound from an increase in new vehicles, battery efficiency degradation rate, lower EV survival rates, vehicle production emissions and recycling rates, and EV deployment rate. These parameters influence the gap in GHG emissions between EVs and conventional vehicles, as well as how quickly EVs can be expected to penetrate the fleet. The sensitivity analysis includes a set of results that simultaneously combines pessimistic (high GHG) or, respectively, optimistic (low GHG) assumptions for electricity grid GHG intensity, EV battery degradation, vehicle survival rates, and vehicle production emissions and recycling.

The sensitivity analysis also examines a potential increase in fleet kilometres travelled associated with a younger vehicle fleet. This increase is based on empirical data showing that newer vehicles are driven more than older vehicles. In the base case, total fleet kilometres travelled are kept comparable across lifespan cap ages, despite the younger fleet.

Table 2 outlines the high and low cases for each parameter used in our sensitivity analysis.

5.7. Calculating fleet level costs per scenario

Our work augments the FLAME model with three modules that combine to calculate fleet level costs (see figure 1). Fleet level costs are calculated by taking FLAME outputs and combining them with cost projections for vehicle purchase, fuel usage, and costs associated with the use phase of the vehicle, as described below. The FLAME outputs considered are the number of vehicles purchased each year (by powertrain type), number of vehicles operating each year (broken down by powertrain type and age), and fleet wide fuel use each year (broken down by fuel type).

5.7.1. Vehicle cost

Vehicle cost projections come from Argonne National Laboratory's Autonomie model and are presented according to Autonomie High and Autonomie Low scenarios [70]. Autonomie costs are based on manufacturing costs and technology progress rather than market forces (i.e. supply and demand or industry pricing strategies). They thus represent system-wide costs rather than private consumer costs. The Autonomie High scenario represents high technology progress, and projects faster decreases in EV costs while the Autonomie Low scenario represents slower technology progress and projects higher EV costs. For vehicle costs, the vehicle purchase cost is applied on a per vehicle sale basis (by vehicle powertrain type, detailed in the supplementary material section S1.2.1). Taxes, fees, and financing costs are not included, under the assumption that they would not be relevant to an abatement cost if the government were to cover the entire cost of implementing the strategy. The vehicle size basis for costs is a small SUV, although sensitivity analysis accounts for vehicle size, with costs projected out to 2050. MY2020 vehicle costs for an ICEV-G are estimated at around 23 000 USD (in 2020 $), increasing to 26 000 by 2050 [70]. For a BEV300 MY2020 vehicle costs are estimated around 57 000 USD (in 2020 $), decreasing to 33 000 by 2050 [70]. End of life residual value is small, but is implicitly captured in the vehicle costs above. Since vehicles are assumed to be scrapped when reaching the lifespan cap, the model assumes residual value is the same regardless of vehicle age at the time of scrappage.

5.7.2. Use phase costs

Vehicle maintenance and repair costs are obtained from empirical data analysed by Martin and published by Your Mechanic [71] and are based on vehicle age. They start at about USD $250 per year for a new vehicle and increase each year capping out at about $2000 after 20 years (costs do not tend to increase at this point as owners typically scrap their vehicles if the maintenance and repair costs get too high) [71]. BEV repair and maintenance costs are estimated to be about 50% lower, based on BEV, PHEV, and ICEV repair and maintenance costs presented by Harto [72]. Details on the data and calculations are in supplementary

Table 2. Parameters considered in sensitivity analysis scenarios for cumulative fleet GHG emissions.

Factor	Reference case/BAU	High GHG emissions case	Low GHG emissions case	Justification
Electricity grid GHG intensity	AEO Reference electricity grid mix GHG intensity with future projections (2020 0.38 kg CO_2e/kWh)	Midcontinent ISO South (MISO) electric grid GHG intensity and projections (2020 0.42 kg CO_2e/kWh), see SM section S1.1.4.3	Northeast Power Coordinating Council/Upstate New York (NYUP) electricity grid GHG intensity and projections (2020 0.12 kg CO_2e/kWh), see SM section S1.1.4.3	MISS electricity grid represents a higher GHG intensity for the USA while NYUP represents a no coal grid and a low GHG intensity for the USA.
AEO scenario	AEO reference (and associated stock, sales, and fuel sources)	AEO low oil price (and associated stock, sales, and fuel source projections)	AEO high oil price (and associated stock, sales, and fuel source projections)	Represent a range of likely future scenarios around vehicle stock and sales without additional policy interventions.
Fleet VKT (vehicle kilometres travelled) growth	Fixed per vehicle VKT	1% annual growth of VKT from 2020 to 2050 (achieved through increasing per vehicle VKT)	1% annual decrease of VKT from 2020 to 2050 (Achieved through decreasing per vehicle VKT)	Represents potential uncertainty around the per vehicle VKT following previous scenarios in Milovanoff *et al* [6].
Behavioural increase VKT from higher concentration of new vehicles	Fleet VKT adjusted to be comparable across all lifespan caps	Fleet VKT increases at empirical rate at which younger vehicles are driven more	Same as reference case/BAU.	Basis of empirical data of VKT by vehicle age. See SM S1.1.2.2.
Electric vehicle battery efficiency degradation	No battery efficiency degradation	Battery efficiency degradation resulting in electric vehicle fuel consumption increase of about 4% per year. See SM section S1.1.1.5.	Same as reference case/BAU.	Improvements in battery technology are reducing their efficiency degradation, and electric vehicles are performing better than expected, but high uncertainty indicates including an upper bound is important.
Vehicle survival rate	TEDB vehicle survival rate for all vehicle types	Thorne *et al* [56] based vehicle survival rates with shorter average lifespans for BEVs and PHEVs. See SM S1.1.2.1.	Same as reference case/BAU.	Some evidence suggests that electric vehicles have lower survival rates than conventional vehicles.
Vehicle production emissions and recycling	Reference case battery starting size and projections, reference material emissions factors, reference battery production emissions of 11.2 kg CO_2e/kg battery, BAU recycling scenario (improvements in total recovery of scrapped materials but no improvement in recycling process).	Larger battery starting size, high GHG emissions factors for battery, 10% increase in primary material emissions factors, BAU recycling scenario, based on Milovanoff *et al* [5].	Smaller battery starting size, low GHG emissions factors for battery, 10% decrease in primary material emissions factors, CL (closed loop) recycling scenario (95% recovery of automotive scrapped materials by 2050) based on Milovanoff *et al* [5].	Combining battery size, emissions factors, and recycling differences gives upper and lower bound emissions from vehicle production. See SM S1.1.1.4, S1.1.4.1, and S1.1.4.2.

(Continued.)

Table 2. (Continued.)

Factor	Reference case/BAU	High GHG emissions case	Low GHG emissions case	Justification
BEV deployment rate	Performed as a breakeven analysis on BEV sales target years from 2035 to 2100, to find the level of battery electric vehicle penetration where vehicle lifespan caps are no longer effective. This breakeven analysis changes the target year of 100% EV sales market shares, while still linearly increasing the sales market share until the target year is reached.			

material section S1.2.2. Insurance costs are not included as they tend to be most correlated to individual drivers, rather than specific vehicles.

5.7.3. Fuel costs

Fuel cost projections are obtained from the 2021 AEO Reference Case for projected fuel costs, except for hydrogen fuel costs, which are based on reported projections from Argonne National Laboratory [52, 70]. Total fuel costs are calculated as the product of annual fleet wide fuel use by year, broken down by fuel type, and cost per fuel type (see supplementary material section S1.2.3).

5.8. Calculating GHG emissions abatement costs

GHG emissions abatement costs are calculated for the BAU scenario and the BEV deployment scenario by considering the fleet level costs of implementing a vehicle lifespan cap, compared to the projected change in GHG emissions associated with the cap (equation (1)). Total costs represent the delta between the net present values of cumulative fleet level costs from 2020 to 2050 with and without the lifespan cap. A discount rate of 3% is selected as it is a typical rate used in such analysis [73],

$$\text{Abatement cost }(\$\text{ per tCO}_2\text{e}) = \frac{(\text{Total cost with lifespan cap}) - (\text{Total cost without lifespan cap})}{(\text{Change in GHG emissions associated with implementing lifespan cap})}. \quad (1)$$

Abatement costs for the BAU scenario and the BEV deployment scenario are assessed under reference, pessimistic, and optimistic assumptions (table 3).

6. Results

This section presents the outcomes of this research, looking at the results of the analyses of the various scenarios and sets of assumptions explored.

6.1. Research question 1—effectiveness of vehicle lifespan caps

The first question that our research sets out to answer is under what conditions would vehicle lifespan caps be effective at reducing GHG emissions from LDVs. To answer this question, we analysed the impact of implementing vehicle lifespan caps under a BAU scenario and eight different technology improvement scenarios. As is detailed below, this work confirms that lifespan caps have limited effectiveness in reducing GHG emissions under a BAU scenario. In contrast, in the technology improvement scenarios that model the deployment of lower carbon intensity vehicles, lifespan caps show potential to meaningfully reduce GHG emissions. GHG reductions are seen to increase when the vehicle lifespan cap is applied only to conventional vehicles.

6.1.1. Analysis of the BAU scenario with 1–30 year lifespan caps

We consider that a cap is effective if it results in a reduction of LDV fleet GHG emissions compared to a base case with no cap. Under a projected BAU scenario, we find that vehicle lifespan caps have limited potential to reduce GHG emissions. The optimal lifespan cap for reducing fleet GHG emissions over the period 2020–2050 was found to be 25 years, with similar GHG reductions achieved with caps in the 24–28 year range. However, in this optimal range only about a 0.1% decrease in cumulative GHG emissions is seen, offset by a 2%–7% increase in primary material demand for metals such as aluminium and steel. Figure 3 shows the cumulative (2020–2050) GHG emissions by life cycle phase for caps of 1–30 years, indicating that although vehicle lifespan caps can reduce GHG emissions from fuel use, these are offset by emissions from the associated increase in vehicle production. Some of the primary contributing factors to the ineffectiveness of lifespan caps under the BAU scenario include the limited improvements in fuel efficiency that are modelled, and the fact that the oldest, most fuel inefficient vehicles are already being driven the least.

Table 3. Sensitivity analysis scenarios for total ownership and GHG emissions abatement costs.

	Reference case	Optimistic abatement cost	Pessimistic abatement cost	Justification
Fuel costs scenario	AEO reference projected fuel costs	High oil price AEO projected fuel costs	Low oil price AEO projected fuel costs	Under high oil prices electric vehicles are preferred and vice versa [74].
Vehicle cost scenario	Autonomie low technology improvement vehicle costs	Autonomie high technology improvement vehicle costs with additional 30% reduction in purchase cost, for each powertrain type.	Autonomie low technology improvement vehicle costs with additional 20% increase in purchase cost, for each powertrain type.	As vehicle cost basis is a small SUV, vehicle price increases and reductions capture the potential price range of vehicles that could be purchased. The scale of increase or reduction represents the difference in vehicle price between a small SUV and the smallest vehicle class, as well as a small SUV and the largest vehicle class [70].
GHG emissions scenario	SAFE fuel efficiency improvement, business as usual electricity GHG intensity, production emissions, and recycling	High fuel efficiency improvement, low electricity GHG intensity, low production emissions, high recycling	SAFE fuel efficiency improvement, EV battery degradation, lower electric vehicle survival rates, high electricity GHG intensity, high production emissions, low recycling	Represents optimistic and pessimistic GHG emissions scenarios [5, 6].

If a high oil price is assumed, which is expected to increase EV adoption, or if a low oil price is assumed, which is expected to decrease EV adoption, the impact of vehicle lifespan caps remains similar. The optimal lifespan cap range widens to 19–27 years when assuming a high oil price, but the percent change in cumulative emissions is still only around 0.2%. Similarly, sensitivity analyses on total fleet VKT, vehicle production emissions, and material recycling show little benefit to creating a vehicle lifespan cap. Even under low vehicle manufacturing and battery production emissions and low electricity grid GHG intensity, lifespan caps of 18–25 years only decrease cumulative emissions about 0.3% (see supplementary material section S1.1.4.3.3 for details) for our BAU scenario. It is clear from our analysis that under a BAU scenario, a vehicle lifespan cap policy on its own is unable to realize a meaningful reduction in GHG emissions from the US LDV fleet.

6.1.2. Analysis of the technology improvement scenarios using 1–30 year lifespan caps

Only when combined with deployment of lower carbon intensity vehicles, such as HEVs, PHEVs, and EVs, do vehicle lifespan caps show potential to meaningfully reduce GHG emissions (i.e. to be effective). The greatest GHG benefit is achieved when the vehicle lifespan cap only applies to conventional vehicles (technology specific). Under a technology specific lifespan cap the cap accelerates alternative vehicle adoption but keeps these alternative vehicles on the road for their full lifetimes (see supplementary material section S2.1.1 for details).

Figure 4 shows the impact of technology specific lifespan caps on cumulative emissions reductions to 2050 from the US LDV fleet under a BAU scenario, and eight technology improvement scenarios (see table 1 for scenarios). Changes in cumulative GHG emissions are relative to the BAU case with no lifespan cap. The orange bars represent the emission reductions achieved by each strategy in the absence of a lifespan cap. Blue bars show each strategy under the 25 year cap that was optimal for reducing GHG under BAU. And green bars show the optimal cap for reducing GHG under each individual strategy.

Under all scenarios that do not include accelerated HEV, PHEV and EV adoption, vehicle lifespan caps continue to show little potential for emissions reduction, as demonstrated by the relatively small differences between the orange, blue and green bars seen in figure 4. Under scenarios that include high deployment of

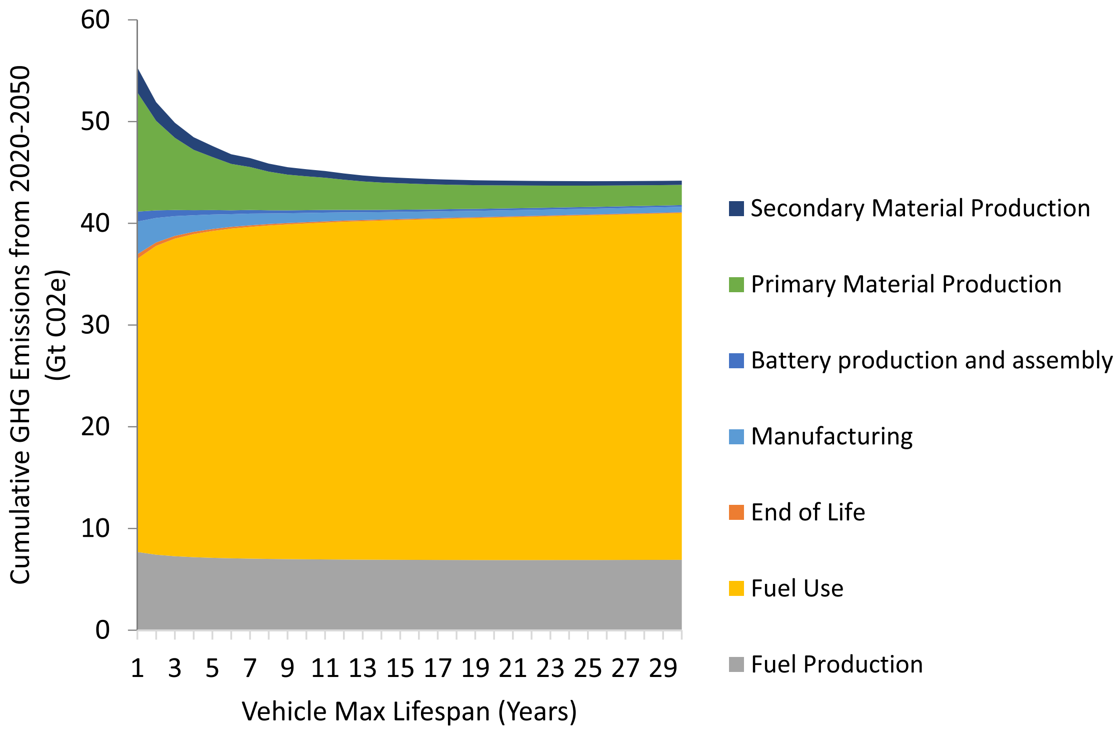

Figure 3. US light-duty vehicle fleet cumulative GHG emissions from 2020 to 2050 by life cycle phase for business-as-usual projections and 1–30 year lifespan caps on conventional vehicles. Primary materials represent raw materials used in vehicles, while secondary materials represent recycled materials. Fuel production includes GHG emissions from gasoline and diesel production for conventional vehicles as well as electricity production for EVs.

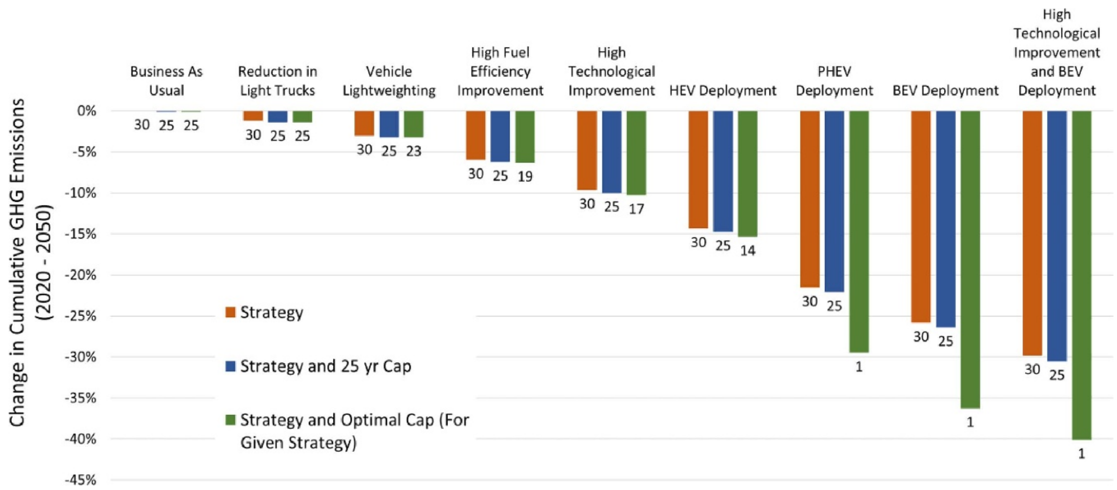

Figure 4. Percent change in cumulative GHG emissions from 2020 to 2050 for the US light-duty vehicle fleet under each of nine scenarios, including the business-as-usual scenario and eight scenarios involving technology improvement strategies. For each scenario the results are presented for three different lifespan cap assumptions: Orange bars—GHG emissions realized through this improvement strategy using the default vehicle lifetime (up to 30 years), Blue bars—GHG emissions realized through this improvement strategy under a 25 year technology specific vehicle lifespan cap vehicles, and Green Bars—GHG emissions realized through the technology improvement strategy and the optimal technology specific vehicle lifespan cap for that strategy. Lifespan caps, in years, are indicated below each bar.

alternative vehicles the addition of a GHG-optimal lifespan cap can lower 2020–2050 cumulative fleet GHG emissions by as much as 1%, 10% and 14% for each of HEV deployment, PHEV deployment, and BEV deployment respectively (difference between orange and green bars). The largest reductions are seen with BEV deployment, and BEV deployment when combined with high technology improvement. Under the accelerated HEV, PHEV and EV adoption scenarios, a 1 year lifespan cap on ICEVs is shown to result in the largest reduction in cumulative GHG emissions, acknowledging that such a cap is not realistic. This result is discussed in the next section.

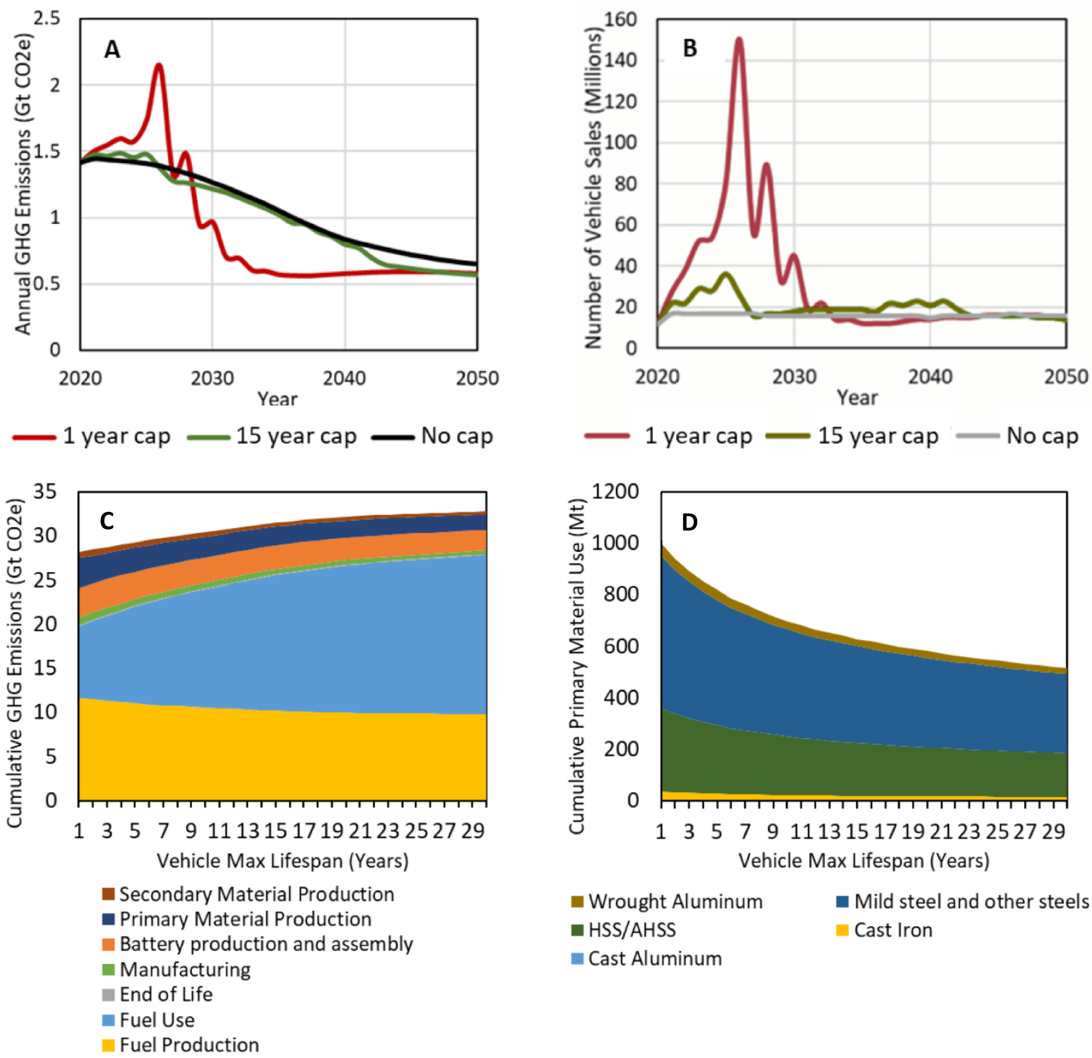

Figure 5. Greenhouse gas emissions, vehicle stock, and material use under 1–30 year lifespan caps for the BEV deployment scenario. (A): Annual GHG emissions for the BEV deployment scenario of 100% BEV300 sales by 2035 and a technology specific lifespan cap under no, 1-, and 15-year caps. (B): Annual vehicle sales for the same scenario, under no, 1- and 15- year lifespan caps. (C): Contributions to cumulative 2020–2050 GHG emissions for lifespan caps of 1–30 years under the same scenario. (D): Contributions to cumulative 2020–2050 material demand under 1–30 year lifespan caps for the same scenario, representing BAU recycling for aluminium and steel. HSS/AHSS: high-strength steel, advanced high-strength steel.

6.1.2.1. Analysis of the BEV deployment scenario using 1–30 year lifespan caps

Having established that lifespan caps are potentially effective in reducing GHG emissions only under scenarios with high deployment of alternative fuel technologies (i.e. BEVs in this paper), we explore the BEV deployment scenario and its impacts in more detail below.

6.1.2.2. GHG emissions, material use, and vehicle sales

Figure 5 shows GHG emissions and material use under the BEV deployment scenario, which sees BEVs representing 100% of new sales by 2035. Figure 5(A) shows the annual GHG emissions under the BEV deployment scenario under various lifespan caps. It shows that under shorter lifespan caps, near term GHG emissions increase but over the long term the cumulative total emissions reductions are maximized. The spikes in GHG emissions seen when using a 1 year lifespan cap are a result of the spike in vehicle manufacturing that is required to replace the large number of ICEVs removed at the end of the transition period; the spikes recur in cyclically as the new vehicles again reach end of life.

The sales of the vehicles used to replace these scrapped vehicles are captured in figure 5(B), which shows annual vehicle sales from 2020 to 2050 under no lifespan cap, a 15 year lifespan cap, and a 1 year lifespan cap. Even under the more modest 15 year lifespan cap there is a substantial increase in annual vehicle sales during the transition period, compared to the scenario without any lifespan cap.

Figure 5(C) shows the cumulative (2020–2050) GHG emissions by life cycle phase for the BEV deployment scenario under a technology specific lifespan cap (i.e. applying only to ICEVs). Here, an illustrative example of a 15 year lifespan cap (with BEV deployment) results in a 4% reduction in cumulative GHG emissions compared to having no lifespan cap. This is equivalent to a 3% reduction from BAU emissions without a lifespan cap, in addition to the 26% reduction from implementing BEV deployment in the form of 100% of sales of BEVs starting in 2035. This is the same scale of impact that fleet wide aluminium maximum lightweighting could have, indicating that vehicle lifespan caps can be effective for reducing GHG emissions through accelerating EV deployment [6].

Figure 5(D) shows the primary material usage of aluminium and steel under 1–30-year lifespan caps. These results show that a 1 year technology specific vehicle lifespan cap with high BEV deployment would almost double primary material needs for metals such as aluminium and steel, while an illustrative 15 year lifespan cap would increase them by 20%.

The increase in short term emissions, material, and vehicle demand under short lifespan caps is largely driven by the model replacing scrapped vehicles with the general market sales proportions for new vehicles. This replacement method was chosen as it is administratively simple, but for shorter lifespan caps it can result in a conventional vehicle being manufactured and scrapped and replaced multiple times in short succession until a 100% EV market share is achieved. This is a limitation of the current modelling method and causes primary material use and GHG emissions to be overstated with shorter lifespan caps. In reality, implementation of this type of policy would require some mechanism to ensure preferential replacement with EVs, rather than the sales market average vehicle type, to increase effectiveness.

Although unrealistic, the results from the 1 year lifespan cap policy option suggest that, from a GHG standpoint, replacing conventional vehicles on the road as quickly as possible would likely result in large cumulative GHG reduction from 2020 to 2050, even when accounting for the considerable emissions associated with new vehicle manufacturing and scrappage. However, it is important to note that this study has not considered the effects of switching to a lower carbon fuel as a complementary measure to decarbonize conventional vehicles, which is likely to reduce the benefits of accelerating a technology-specific vehicle lifespan cap.

6.1.2.3. Sensitivity analysis: impact of technology specific lifespan cap and BEV deployment on GHG emissions
Sensitivity analysis on the BEV deployment scenario using a technology specific lifespan cap shows that under all but the worst circumstances the optimal cap age to maximize GHG emissions reductions remains 1 year (see supplementary material section S1.1.4.3.4). This indicates that in all but the worst cases for BEVs, there is still a GHG reduction benefit in accelerating their deployment.

Figure 6 shows the change in absolute GHG emissions achieved by implementing 15 year and 1 year lifespan caps under the BEV deployment scenario using the assumptions for high GHG emissions from electrical production and low GHG emissions that are specified for sensitivity analysis (see table 2). SM section S1.1.4.4.3 includes a complementary figure that shows the cumulative GHG emissions for each parameter under the high and low GHG emissions assumptions.

The sensitivity analysis reveals that the effectiveness of lifespan caps is reduced when using assumptions such as fleet-wide per-vehicle VKT reductions, EV battery efficiency degradation, shorter BEV lifespans, high production emissions and low recycling rates, and high electricity grid GHG intensity. However, lifespan caps still offer GHG reductions relative to the base case, even under these negative assumptions. The only exception is when there is a large rebound effect due to higher VKT of new vehicles under a moderate (15 year) lifespan cap. In the nine lifespan cap scenarios evaluated, it is assumed that there is no increase in the VKT of newer vehicles. But historical data suggest that newer vehicles are typically driven more kilometres annually. Therefore, in this sensitivity analysis we test the impact on GHG emissions of assuming an empirical distribution of VKT across vehicle ages based on historical data. Under this assumption we find that fleet renewal results in higher overall fleet kilometres driven due to the greater proportion of young vehicles in the fleet, and thus higher total GHG emissions. This increase in VKT is found to negate the GHG reductions generated by a 15 year lifespan cap. However, under an accelerated lifespan cap (i.e. 1 year) these higher emissions are offset by the faster penetration of lower emitting vehicles.

Given that a 1 year lifespan cap results in the lowest GHG emissions under the high BEV deployment scenario it is important to test whether this conclusion holds when less aggressive assumptions regarding BEV deployment are modelled. This is accomplished by varying the 100% BEV deployment target year to simulate different BEV deployment rates and assessing the resulting effectiveness of vehicle lifespan caps. All results are simulated from 2020 to 2050. Table 4 shows results when different prospective target years for reaching 100% BEV sales are modelled. The associated BEV sales share in the year 2035 is provided. The table shows the GHG reductions achieved in each case when using both a 15 year lifespan cap and a lifespan cap that results in the lowest GHG emissions. The table also provides the % reduction in GHG emissions achieved by implementing that cap. A BEV sales market share of at least 26% by 2035 (corresponding to 50%

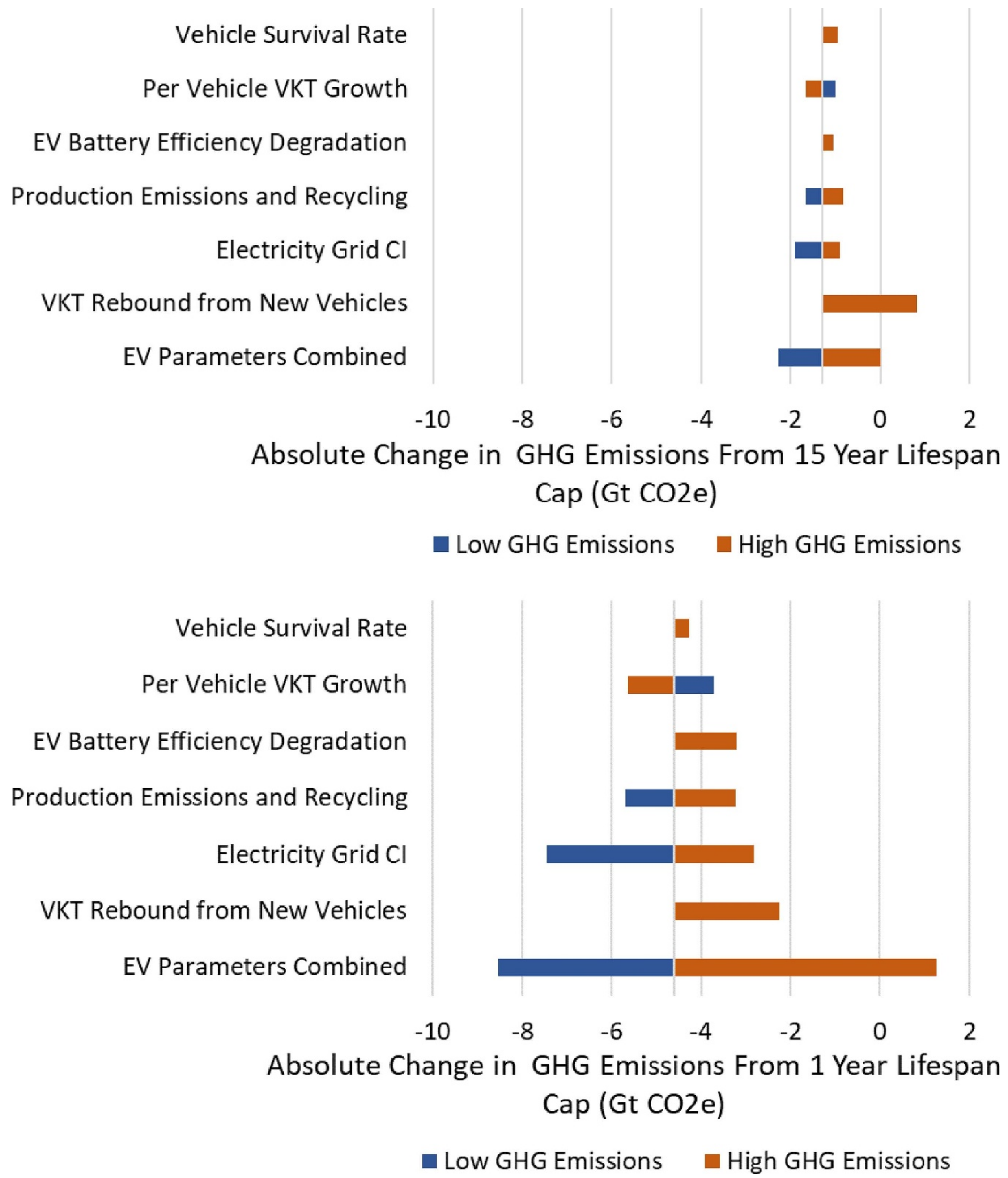

Figure 6. Tornado plot showing results of sensitivity analysis on cumulative 2020–2050 GHG emissions from the BEV deployment scenario under a 15-year (top panel) and a 1-year (bottom panel) lifespan cap.
Notes: the y-axes are set by the emissions reductions based on the BEV deployment scenario under a 15-year lifespan cap (cumulative reduction of 1.3 Gt CO_2e) and 1 year lifespan cap (cumulative reduction of 4.6 Gt CO_2e) with the default value (reference case/BAU) for each sensitivity case. EV parameters combined refers to the EV specific survival rate, per vehicle VKT growth, EV battery efficiency degradation, production emissions and recycling, and electricity grid GHG intensity (indicated as electricity grid CI (carbon intensity) in figure) parameters combined. Note that this graph shows changes relative to the no-lifespan cap scenario for each case (supplementary material figure S30). Thus, sometimes the 'high GHG emissions' case (in orange) leads to a greater impact of the lifespan cap (i.e. results are more negative) than the 'low emissions' case (in blue), even though total fleet emissions would still be higher in such cases.

by 2050) would have to be achieved for vehicle lifespan caps to result in greater than 1% GHG emissions reductions at the optimal cap compared to no cap. A BEV sales market share of at least 38% by 2035 (corresponding to 75% by 2050) would have to be achieved for the 15 year vehicle lifespan caps to result in greater than 1% GHG emissions reductions compared to no cap. Under current policies, the 2023 AEO reference scenario still projects alternative vehicles (primarily BEVs) to comprise only about 25% of new vehicle sales by 2035, which thus necessitates other policy measures to deal with legacy vehicles in the fleet.

Single vehicle analysis shows similar trends to the fleet level analysis. GHG emissions from 2020 to 2050 are minimized by early replacement of ICEV with EVs. Early replacement of a conventional vehicle with a new conventional vehicle shows little benefit. Early replacement of an EV with another EV increases total

Table 4. Sensitivity of GHG emissions savings with a 15-year lifespan cap and with an 'optimal' lifespan cap to sales market share of BEVs in 2035 with the 100% BEV sales target year ranging from 2035 to 2100. Results are always for the period from 2020 to 2050; sales target years are used only to set the pace of BEV adoption during the simulated rate. Extended version of table available in supplementary material S2.1.4.

100% BEV deployment target year	% BEV sales in target year	% Sales market share of BEV by 2035	%Cumulative GHG emissions reduction (2020–2050) at 15 year lifespan cap compared to no cap	Lifespan cap year with highest GHG savings	%Cumulative GHG emissions reduction (2020–2050) at optimal lifespan cap compared to no cap
2035	100%	100%	4.0%	1	14%
2040	100%	75%	3.2%	1	14%
2050	100%	50%	1.9%	1	12%
2060	N/A	38%	1.2%	1	9%
2070	N/A	31%	0.8%	1	6%
2080	N/A	26%	0.5%	1	3%
2090	N/A	22%	0.3%	19	0.4%
2100	N/A	20%	0.2%	19	0.3%

GHG emissions. The single vehicle analysis also confirms that the better the fuel efficiency of the replacement vehicle, the lower the cost to the driver and the lower the cumulative GHG emissions. This suggests that the preferred strategy for a lifespan cap would be through a targeted replacement, to accelerate fleet modernization with advanced and efficient powertrains like EVs, HEVs, PHEVs, and the most fuel-efficient vehicles available—rather than a blanket incentive to scrap all vehicle types. Details of the single vehicle analysis are presented in supplementary material section S2.3.

6.2. Research question 2—cost and cost-effectiveness of vehicle lifespan caps

The second question that our research sets out to answer is whether vehicle lifespan caps would be a cost-effective mechanism for reducing GHG emissions from LDVs. To answer this question, we analysed both the BAU scenario and the BEV deployment scenario using three sets of cost assumptions—reference, optimistic, and pessimistic. This work finds that under both the BAU and BEV deployment scenarios a vehicle lifespan cap delivers GHG emission reductions at reasonable abatement costs only under the optimistic set of assumptions. Overall, the cost of GHG reductions realized through lifespan caps are found to be comparable with the upper end of current estimates of the social cost of carbon.

6.2.1. Analysis of the BAU scenario using three cost assumptions

The BAU Scenario is run through the FLAME model under the three sets of cost assumptions used in this work's sensitivity analyses—a reference case, an optimistic abatement cost case, and a pessimistic abatement cost case (see table 3). This analysis finds that under the BAU scenario a lifespan cap only delivers GHG reductions at reasonable abatement costs under the optimistic set of assumptions.

When the reference cost assumptions were used (see table 3), lifespan caps increased total fleet level ownership costs, while effectively providing no GHG emissions benefit (see supplementary material section S2.2.1 for detailed results). For the caps ranging from 24 to 28 years, fleet level private costs increased by 1%–4%, while there were minimal GHG emissions benefits. Under shorter caps, such as 15 years, fleet level costs went up by as much as 20%, and cumulative GHG emissions started to increase (at first by less than 1%, then more as the lifespan cap year gets lower).

Under the pessimistic cost case, lifespan caps only increased fleet level costs and GHG emissions, suggesting that a vehicle lifespan cap is unlikely to be a viable policy option under these unfavourable circumstances. On the other hand, under an optimistic set of assumptions—combining the effects of lower cost vehicles, low production emissions, high material recycling, high fuel consumption improvement, and low carbon intensity electricity—some lifespan cap options offered GHG benefits at a more reasonable abatement cost (see supplementary material section S2.1.1).

6.2.2. Analysis of the BEV deployment scenario using three cost assumptions

These findings were largely mirrored (and scaled up) when the BEV Deployment Scenario was analysed using the three cost assumptions, with a vehicle lifespan cap only shown to deliver cost-effective GHG emissions reductions under the optimistic set of cost assumptions.

Figure 7 shows (A) the total fleet costs, (B) cumulative GHG emissions and cost-effectiveness, and (C) different lifespan caps under a 100% BEV deployment by 2035 scenario for the reference, optimistic and pessimistic sets of cost assumptions. The right-hand side of diagrams A and B (i.e. the 30 year cap) show the fleet cost and emissions in the absence of a cap, which is used as the reference for calculating the change in

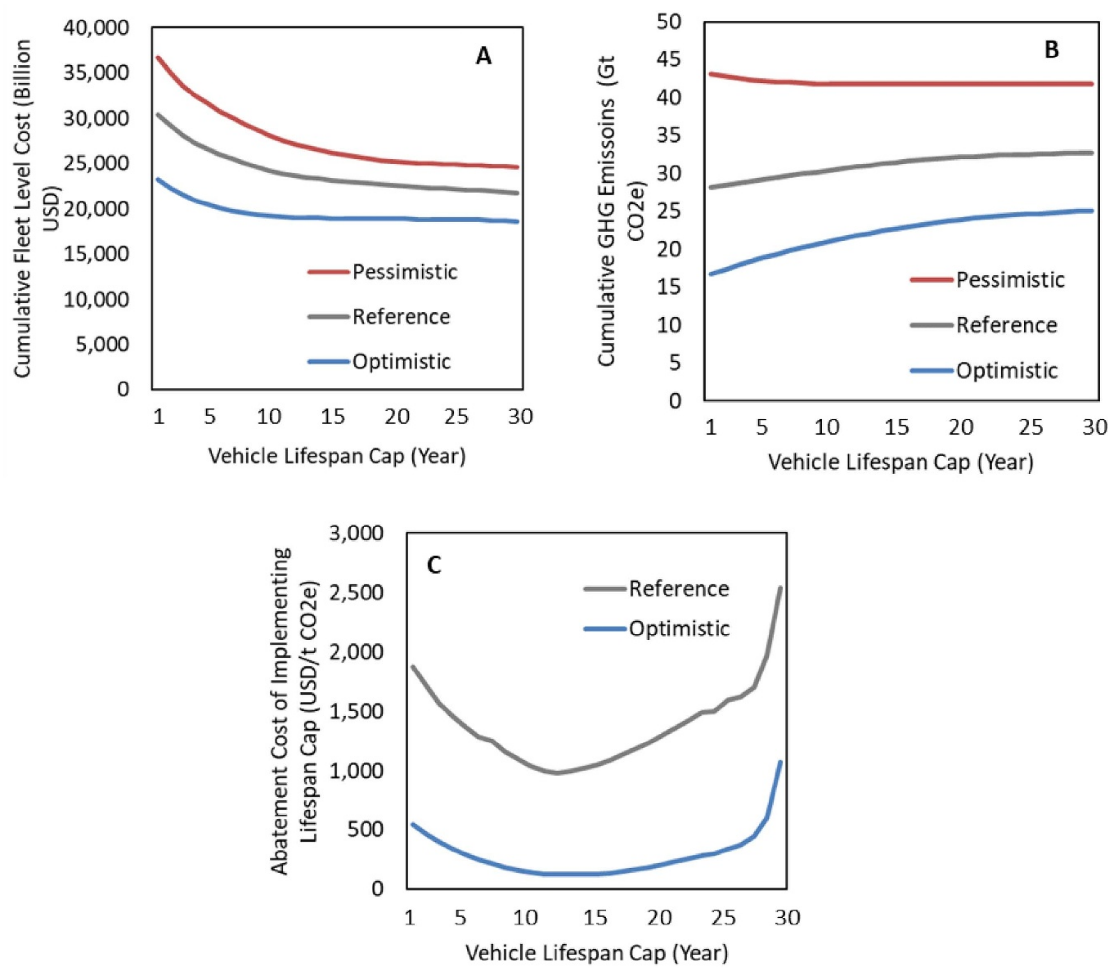

Figure 7. Fleet level costs, fleet level GHG emissions, and abatement costs under 1–30 year lifespan caps for the BEV deployment and the pessimistic, reference, and optimistic cost scenarios. Figure (A) shows the present value of the cumulative 2020–2050 fleet level total ownership costs. Figure (B) shows the cumulative 2020–2050 fleet GHG emissions. Figure (C) shows the abatement cost of implementing a lifespan cap in addition to BEV deployment (abatement cost of BEV deployment not in the cost, just the lifespan cap implementation). The pessimistic scenario has been left out of C due to exorbitantly high abatement costs as there are almost no GHG emissions reductions. Scenarios are as defined in table 3.

costs and emissions as a result of introducing a lifespan cap. These are subsequently used as inputs for estimating the abatement costs (Panel C) in USD/t CO_2eq.

Under all three sets of cost assumptions, fleet level costs increase as the lifespan cap becomes lower (figure 7(A)). For the reference case, fleet level costs increase by as much as 40% (1-year cap, left side of Panel A) when a lifespan cap is added compared to having no lifespan cap. Although not shown in the figure, the BEV deployment reference case fleet level costs are about 14% higher than the BAU scenario without a lifespan cap, largely driven by the high BEV purchase cost (see supplementary material section S2.1.1). Figure 7(C) shows the abatement costs for the reference and optimistic cases. The pessimistic case is not included, given that it has an exorbitant abatement cost due to the limited GHG benefit that it offers.

Note that the abatement costs in figure 7(C) are specifically for the GHG reductions realized through the addition of a lifespan cap, and are compared to BEV deployment without a lifespan cap. There are also costs and emission reductions from BEV adoption compared to BAU, but which cannot be seen in this figure. In both the optimistic and reference cases the lowest abatement cost occurs with a 12 year lifespan cap. Under the reference case this coincides with a 6% reduction in cumulative GHG emissions and a 9% increase in cumulative fleet level total ownership costs relative to BEV deployments without a lifespan cap. This translates to about \$980/t CO_2e abatement cost just from the introduction of lifespan caps. Under the optimistic case, lifespan caps of 11–15 years result in minimal abatement costs, implying that a lifespan cap has the potential to be cost-competitive when complemented by other measures. It is important to note, however, that the abatement cost here is associated with the introduction of a lifespan cap, and not the cost due to 100% BEV deployments by 2035, so there will be other costs associated with this abatement option (see supplementary figure S44).

6.2.3. Are vehicle lifespan caps cost-effective compared to other carbon reduction mechanisms?
When compared to the social cost of carbon, the abatement costs shown in figure 7(C) are quite high. The social cost of carbon estimates the net present value of social damages from emissions of an additional ton of CO_2 [75]. Under the Biden Administration, the social cost of carbon is calculated with a 3% discount rate and sits at \$51/tCO_2e [76], much lower than the abatement cost of vehicle lifespan caps found in this paper for all but the most cost-effective cap years within the optimistic scenario. However, other estimates of the social cost of carbon can range from \$200 to \$800/tCO_2e, the upper end of the range being much closer to the average cost-effectiveness values in this work [77, 78].

When compared to the static costs of policies targeting GHG emissions reductions presented by Gillingham and Stock [75], policies such as reforestation, wind energy subsidies, gasoline taxes, and corn ethanol all have much lower abatement costs, but lifespan caps in addition to BEV deployment could fall into similar ranges of low carbon fuel standards, and solar PV subsidies, which sit at USD \$100–3000 /tCO_2e and USD \$150–2200/tCO_2e (adjusted to 2020 dollars using the CPI) [75]. Another point of comparison is direct air carbon capture technologies, whose abatement costs are assumed to sit at \$100 to \$1000/tCO_2e, and again we find that only the upper end values are in line with the cost-effectiveness values calculated for the reference case lifespan caps [79–81].

7. Discussion

7.1. Effectiveness

This work shows that for BEV deployment, vehicle lifespan caps have the potential to be effective at reducing cumulative GHG emissions through accelerated BEV penetration in the fleet. An illustrative 15 year lifespan cap is estimated to have the potential to reduce cumulative 2020–2050 GHG emissions by 1.3 Gt (∼3% when compared to the BAU scenario), and by 2050 can reduce annual fleet GHG emissions by an additional 0.1 Gt per year (∼15% when compared to high BEV deployment with no lifespan cap). For comparison, Chen *et al* [82] found that a corn ethanol mandate that forces maximum ethanol use in vehicles could result in a similar scale of reduction in LDV emissions (also 1.3 Gt), but on a shorter timescale (2016–2030). GHG emissions reductions scenarios for LDVs covered by Kromer *et al* [12] estimated that annual reductions by 2050 could be achieved on a scale of 0.1–0.2 Gt from biofuels, 0.1–0.2 Gt from a clean electricity grid, 0.1–0.2 Gt from vehicle weight reductions, 0.1–0.4 Gt from reductions in VKT, and 1.1–1.5 Gt from vehicle technology improvements. Compared to an ethanol mandate as modelled in [82] a lifespan cap is seen to be less effective. But compared to the mechanisms examined by Kromer *et al* [12] a lifespan cap is seen to be more effective. The outcomes in this work and the two comparators presented are not directly comparable due to differences in methods, assumptions and underlying models, but the comparisons provide some indication of the scale of GHG emissions reductions projected under vehicle lifespan caps in this work.

While the primary focus of this work is at the fleet level, analysis presented in supplementary material sections 1.3 and 2.3 indicate that these results also hold for single vehicle replacement, where early retirement of ICEVs can reduce emissions under most sets of assumptions, but only when they are replaced by BEVs.

7.2. Cost-effectiveness

The abatement costs determined in this work tend to be high compared to estimates of the social cost of carbon and other GHG emissions reduction options, although under the optimistic scenario the lifespan cap is of similar magnitude to some social cost of carbon measures. This indicates that lifespan caps are unlikely to be cost-effective in the near-term but may become more so if underlying factors see large improvement (e.g. improved fuel efficiency of electric vehicles and reduced grid GHG intensity). The cost may also become necessary if typical policy levers are not moving consumers sufficiently quickly toward EVs—or other low carbon options like alternative fuels and public transit.

8. The limits of this study

The authors would like to highlight the following limits to the research undertaken:

- The effectiveness of a vehicle lifespan cap is influenced by additional factors beyond the scope of the current study, including but not limited to the implementation method chosen, consequential effects on the electricity grid from BEV deployment (see immediately below), and changes in vehicle ownership rates and driving behaviours that may be induced by the cap. In particular, the choice to model exogenous vehicle ownership rates and technology market shares overlooks the potential for a lifespan cap to induce large systemic changes that would need to be captured via a more complex model incorporating market dynamics and feedback loops. Thus, instead of predicting the full set of changes that may be induced by a lifespan cap, our results should be interpreted as examining a specific set of potential end-states for the vehicle system with a focus on representing technologies rather than behavioural outcomes.

- For BEVs, available grid infrastructure has limitations. Accelerated EV deployment without accompanying grid infrastructure changes may result in increased GHG emissions from the electricity supplied to BEVs. This is referred to as the marginal emissions associated with additional EVs on the road. These marginal emissions and charging schedules have not been considered in this work, despite potentially limiting how effective BEVs are at reducing emissions [83, 84]. Moreover, the GHG and monetary cost to build infrastructure required for BEVs has not been accounted for in this work, which may lead to underestimation of the GHG emissions associated with high BEV deployment [85]. The inclusion of these aspects is complex and beyond the scope of the current study. Co-planning of charging infrastructure and systems to match EV deployment rates will be important for the success of EVs and lifespan caps.
- The abatement costs presented must be considered highly uncertain due to the difficulty of projecting future costs. High sustained oil prices due to global geopolitical uncertainty have the potential to further favour electric vehicles over conventional vehicles, due to lower operating costs, while a drop in oil prices could be more favourable for conventional vehicles. Moreover, abatement costs in this study do not account for costs associated with infrastructure development.
- The implementation method in this study is blunt, forcing vehicles off the road and replacing them with the average sales market share vehicle. Different implementation methods are possible, and each will yield different results. For example, subsidies can be used to encourage early vehicle replacement, rather than forced vehicle replacement, similar to those studied in Keith *et al* [22]. Keith *et al*'s [22] subsidy approach found similar abatement costs, but lower cumulative GHG emissions reductions than in this work. These lower cumulative reductions occur because a much lower number of vehicles are being replaced in the subsidy scheme than in the forced replacement scheme. Another implementation option is to keep the blunt lifespan caps, but target replacement of only the worst vehicles with the best available vehicles, with or without government subsidy.
- This study found that lifespan caps are only effective under a scenario of rapid BEV deployment. A cap could also be effective under other measures resulting in substantially reduced emissions among new vehicles, such as extreme rates of technological improvement to gasoline vehicles [47] or hydrogen FCVs [86], but these were not considered here. Similarly, lifespan caps may have added GHG benefits if they induce modal shift away from private vehicles or enhanced consumer preference for EVs. Such behavioural changes are beyond the scope of the present study.
- On the other hand, wide-scale deployment of low-GHG drop-in fuels may obviate the need for accelerated vehicle replacement [87] and would therefore undermine any benefits of lifespan caps compared to the results above.

9. Other considerations and future work

9.1. Feasibility

The current study examines the impacts and costs of vehicle lifespan caps, without consideration for the feasibility of the policies being modelled. However, choices made regarding the implementation of a vehicle lifespan cap impact not just the effectiveness, but also the real-world feasibility of a policy. While a blunt implementation policy is a useful construct from which to gain academic insight on the effectiveness and efficiency of vehicle lifespan caps under various scenarios, it would be extremely difficult to implement such a policy in today's world, with perhaps the exception of authoritarian regimes. By contrast, a form of vehicle lifespan cap that relied on subsidies to encourage a desired rate of vehicle replacement may deliver lower cumulative GHG emissions but be more feasible to implement. Given that the potential benefits of a lifespan cap policy are only realized if the policy is implemented in the real world, it will be important to extend this analysis of the effectiveness and efficiency of such policies in a way that incorporates considerations of feasibility.

Several feasibility challenges exist for a vehicle lifespan cap as modelled in this research, both in the political and physical implementation spheres. Politically, without large subsidies a lifespan cap as modelled here has the potential to impose a significant financial burden across a large fraction of vehicle owners, which from a political perspective would be highly unpalatable. Moreover, this type of policy may be seen as wasteful from a cost and material use perspective, and may increase anxiety around EV adoption. Future work should explore equity considerations, public acceptance as well as administrative complexity associated with implementation of any lifespan cap-related policies.

On the physical implementation side, expected constraints due to the volume of EV deployment will be faced on an accelerated scale under this type of policy. These expected constraints include infrastructure limits, with US infrastructure potentially unable to respond fast enough to support accelerated deployment of EVs, and resource availability, which threatens to limit the rate of EV production. Even at lower EV deployment rates than those under the lifespan caps modelled here, authors have noted concerns regarding the infrastructure needed to support EV adoption. Engel *et al* [88] note a gap between the demand and supply of electricity for charging EVs. Jiang *et al* [89] use a case study to show how distribution networks may limit EV adoption. Lopez-Behar *et al* [90] cover challenges to installing charging infrastructure in multi-unit residential buildings. At accelerated deployment rates, each of these challenges becomes more pronounced and future work should, in parallel, explore infrastructure impacts of any vehicle cap policies.

Multiple battery and electric motor materials, including natural graphite, lithium, cobalt, dysprosium, terbium, praseodymium, and neodymium have been discussed as supply risks for EV production due to their critical nature in EV production and the large increase in expected demand, which will outpace historic supply trends [91–93]. Ballinger *et al* [93] finds that lithium, cobalt, and graphite supply chains face issues such as regional concentration, geopolitical instability and risk, and growth in competing markets, which may make it challenging to meet less aggressive EV deployment rates than those seen under lifespan caps. New battery technologies and improvements of lithium ion batteries may mitigate some of these issues [93, 94]. Our previous research that incorporated battery critical material demands into FLAME [46] could be integrated with lifespan cap considerations to provide a deeper understanding of the impact of lifespan caps on critical material demand.

9.2. Additional environmental impacts

Vehicle lifespan cap policies will likely reduce criteria air pollutants (CAPs) emissions volumes and alter their spatial distribution. This will occur both through early retirement of older vehicles whose catalytic converters are degraded [21, 40, 41], and also through accelerated deployment of electric vehicles which are expected to have lower overall CAP emissions [95–97].

Despite expected benefits from BEV deployment, these vehicles have also been shown to negatively impact human toxicity, freshwater eco-toxicity, and freshwater eutrophication [20, 98]. Verma *et al* [98] summarizes six studies that all find higher human toxicity for BEVs than for ICEVs. Higher human toxicity levels come from larger use of metals, chemicals, and energy in powertrain and battery production [98]. With accelerated EV deployment, these negative impacts will also increase, and although not captured within the current work, are important considerations for future work.

9.3. Equity

Equity considers the distribution of benefits and impacts of a policy. The GHG and CAP emissions benefits of the lifespan cap policy are more likely to positively impact marginalized communities. However, the policy's negative impacts including higher vehicle costs, and social and health impacts related to metals and mining, are also more likely to disproportionately negatively impact marginalized communities.

GHG emissions unequally impact different countries, and even regions. The social cost of carbon is unequal across different countries, with countries that incur larger fractions of the global cost identified as India, China, Brazil, the United Arab Emirates, Saudi Arabia, and the United States by Ricke *et al* [78]. The IPCC has identified that socially and economically disadvantaged and marginalized people are disproportionately affected by climate change [99]. CAPs from transportation are also known to affect low-income and disadvantaged communities disproportionately, due to a higher likelihood to live near areas of high traffic [95]. Globally, and locally, vehicle lifespan caps have the opportunity to bring benefits in the areas of CAP and GHG emissions to disadvantaged communities.

At the same time, and depending on the implementation method, rising vehicle ownership costs will disproportionately affect low-income households. Analysis of the 2017 National Household Travel Survey by Bauer *et al* [100] reported that over 10 million US households do not own a car, typically due to physical or economic constraints, and that lower income households who do own cars spend larger proportions of their income on vehicle related expenses. Bauer *et al* [100] also showed that households with annual incomes below \$25 000 purchase vehicles when they are 7.2 years old on average, while households with annual incomes greater than \$150 000 purchase vehicles when they are 3.9 years old on average, indicating that, unless increases in total ownership costs are covered by the government, these lower income groups will be more likely to be forced to retire their vehicles earlier, and carry a higher burden of more frequent replacement costs. The Victoria Transport Policy Institute [101] defines transportation affordability as households being able to spend less than 20% of their budget on transport, but 2017 National Household Travel Survey data analysis by Bauer *et al* [100] shows that American households with income less than \$50 000 already spend more than 20% of their income on vehicle ownership. As these lower income households face higher vehicle ownership costs, more households may be priced out of vehicle ownership, creating social exclusion and mental health impacts, while limiting access to higher paying jobs, health care, and food [100, 102]. Moreover, social and health impacts from mining, including rising levels in human toxicity, will affect the countries of origin of the materials more deeply than the US.

Equitable implementation of a lifespan cap policy will require consideration of these factors, and would benefit from additional quantitative analysis as well as more detailed equity analysis to capture potential unintended consequences. Improvements to personal transportation affordability could also be achieved through appropriate investments and planning in public transit.

10. Conclusion

This work augments the US LDV fleet LCA model, FLAME, with new capability related to the implementation of potential vehicle lifespan caps. We find these vehicle lifespan caps are likely not worthwhile for the US LDV fleet from the perspectives of reducing GHG emissions (effectiveness) or cost-effectiveness except when they are combined with high EV deployment. Using vehicle lifespan caps as a tool to accelerate EV adoption has relatively high GHG abatement costs and could also amplify some of the negative effects of EV adoption including increased usage of critical materials and increased ecotoxicity related to battery production. However, co-planning of vehicle lifespan caps alongside complementary strategies, such as electricity grid emissions intensity reductions, vehicle fuel consumption improvements, and vehicle production emissions reductions can substantially boost the GHG emissions benefits, while reducing abatement costs. Overall, vehicle lifespan caps must be carefully considered as they will accelerate both the benefits and costs of the new vehicle technologies being developed, and are best positioned as part of a larger integrated strategy for tackling transportation GHG emissions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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