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Closing the GHG mitigation gap with measures targeting conventional gasoline light-duty vehicles – A scenario-based analysis of the U.S. fleet

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HIGHLIGHTS

- Examined GHG mitigation measures targeting gasoline vehicle (ICEV-G) technology
- Higher efficiency, hybridization & downsizing help ICEV-Gs meet GHG targets
- Such measures can reduce cumulative fleet GHG emissions through 2050 by 5 to 30%
- Plausible ICEV-G measures can delay need for full electrification by 5–25 years
- Effective policy requires both technological improvements and behavioral changes

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ABSTRACT

Despite international efforts to increase the adoption of alternative fuel vehicles, global gasoline internal combustion engine vehicles (ICEV-Gs) sales are projected to remain strong for the coming decades, with electric vehicles (EV) sales remaining well below 50% under International Energy Agency projections for 2030. The current study analyzes the cumulative reduction of greenhouse gas emissions that can be obtained by 2050 from policies targeting these gasoline powered vehicles. The analysis is applied to the case of the U.S. light-duty vehicles (LDV) fleet, a representative country with a large LDV fleet and slow EV penetration; the work considers technological, decisional and behavioral solutions. Technological pathways include fuel economy improvements, vehicle lightweighting and a greater provision of ethanol blends. Decisional pathways include purchasing decisions related to vehicle size and relative (best-in-class) fuel economy among available models. Behavioral pathways include improvements in driving habits.

This study demonstrates the transitional and complementary role to fleet electrification that ICEV-Gs can play to meet climate targets, starting from vehicle models in the market today. A scenario-based analysis confirms that effective and diverse mitigation pathways targeting ICEV-G decarbonisation may lessen the need for aggressive fleet electrification rates – reducing the required cumulative electric vehicle sales through 2050 by at least 10% and by as much as 98% under extreme scenarios in the U.S. The analysis also identifies the limit of the ICEV-G fleet decarbonisation at 40% of cumulative lifecycle emissions from 2021 to 2050 in a very optimistic scenario, suggesting that these measures can complement but not replace the need to develop alternative fuels and powertrains.

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1. Introduction

The transportation sector accounted for roughly 15% of global greenhouse gas (GHG) emissions in 2020 [1]. About 50 % of the corresponding CO_2 emissions were attributed to the passenger transport fleet (light-duty vehicles (LDV) and buses) [2], which predominantly have internal combustion engines powered by conventional fuels [3].

Electric vehicles (EVs) are viewed as a promising and scalable solution to the problem of LDV fleet GHG emissions [4]. A Net-Zero emissions trajectory by 2050 for the LDV sector is estimated to require 64% and 100% of the LDV sales to be EVs in 2030 and 2050, respectively [5]. This extreme fleet electrification is projected to cause surges in the demand for 1) critical materials [6], 2) electricity consumption [7], and 3) infrastructure upgrades [8,9]. While EVs achieved a record market share of 9% of new LDV sales in 2021 [10], the International Energy Agency projects that 2030 EV sales shares would optimistically reach 35% under the announced pledges scenario and only 22% under the existing policies scenario [6]. Without additional measures, these rates would be insufficient to ensure timely decarbonization of the LDV fleet. Further, 85 % of global EV sales in 2021 were in Europe and China [10]. EV sales have been slow in other markets such as the U.S., Canada, Australia, Japan, among others due to a range of conditions including inadequate charging infrastructure and high capital costs [10] and non-existent in low-income countries, which rely heavily on second-hand vehicle imports from wealthier countries [11]. Owing to the above, achieving aggressive fleet electrification rates will be challenging.

Pathways complementary to fleet electrification must be considered to prevent, from an early stage, the generation of GHG emissions beyond the allowable carbon budget for the LDV sector. In particular, measures targeting efficiency improvements of internal combustion engine vehicles (ICEVs) are of notable importance given these vehicles' ongoing dominance for passenger transport in many countries around the world. Even regions such as the European Union that previously aimed to phase out ICEVs have since reversed course, albeit alongside a greater push for carbon neutral fuels [12]. Thus, improvements in ICEVs can play a role either in reducing pressure on as-yet-undeveloped supply chains for carbon neutral fuels or in the transition period toward alternative powertrains.

At the vehicular level, studies have evaluated the impacts of mitigation pathways such as a change in powertrain technology [13], change in fuel production pathways [14], vehicle lightweighting [15,16], vehicle downsizing [17], fuel economy improvements [18,19], driving behaviors [20], among others. At the fleet level, several studies have assessed the life cycle GHG emissions mitigation potential of a selection of pathways. The underlying objective of these fleet-level studies was to investigate where efforts would be most effectively placed with respect to mitigating GHG emissions and provide insights for decision makers. In the most recent example, Woody, Keoleian and Vaishnav (2023) demonstrated via a fleet-based LCA modeling at a state level in the U.S. that aggressive vehicle electrification and grid decarbonization need to be coupled with additional strategies (e.g. improving fuel economy, fleet downsizing, early vehicle retirement, reducing travel demand) to meet short term decarbonization targets [21]. Previously, Garcia and Freire (2017) conducted a review of 29 fleet-based life cycle assessment studies [22]. They found that the studies focused on alternative powertrain technologies and otherwise only considered two interventions, specifically fuel consumption improvements attributed to technological progress and vehicle weight reduction. Table SI.1 of the Supplementary Information (SI) extends that analysis, confirming that no study has specifically explored the potential role ICEVs could play in meeting climate targets [23–38] (details pertaining to these citations including a list of mitigation measures assessed and a non-comprehensive summary of the main findings are available in Table SI.1.). No prior study has specifically examined the question of how these strategies interact, nor explicitly how they might reduce the burden on EV penetration under a set GHG budget.

This study addresses these gaps and investigates how a focus on complementary measures targeting ICEVs can assist in decarbonizing the LDV fleet and lessening the burden on the penetration of EVs or novel low-carbon fuels. This is a critical step both to demonstrate the role of complementary strategies, and to offer policymakers more flexibility in the decarbonization vision (and associated impacts) than is currently offered by EV-only or EV-predominant strategies [34]. We apply this analysis to the case of the U.S. LDV fleet due to the public availability of an up-to-date fleet-based life cycle assessment model and the ease-of-access to detailed data needed for the modeling. Further, the U.S. LDV fleet is a compelling case to evaluate as it is the second largest market after China and the EV rollout remains modest (averaging 7% of new LDV sales in 2022 [39]), despite policies and initiatives enacted to promote the manufacturing and adoption of this powertrain technology. The Energy Information Administration's Annual Energy Outlook projects that EVs will account for only 10%–24% of the total new vehicle sales in the U.S. in 2050 under the current policy mix for scenarios of low and high oil prices, respectively [40].

We evaluate the individual impacts of a number of pathways targeting the gasoline portion of the fleet on the U.S. LDV fleet life cycle GHG emissions from 2021 through 2050, along with their joint impacts – which are not strictly additive. We then determine the reduction of GHG emissions that may be obtained for scenarios representing potential future development of the U.S. LDV fleet. We then assess how the enhancements to the ICEV-G stock resulting from the pathways evaluated in this study (e.g., improved fuel economy, smaller-sized vehicles, etc.) can reduce the fleet electrification rates and the life cycle carbon intensity (CI) of gasoline needed to remain within a carbon budget consistent with a 2 °C target. By analyzing the effectiveness of mitigation pathways other than fleet electrification, we put forward insights on the transitional and complementary role ICEV-Gs can play to meet climate targets of the LDV fleet.

2. Methods

This paper investigates the GHG mitigation potential of strategies targeting conventional gasoline LDVs in the U.S. fleet through 2050. We only consider six pathways directly linked to ICEV-Gs and that are plausibly available for immediate implementation. Thus, for the purpose of this analysis, we deliberately exclude other potential strategies such as those that rely on changes in travel demand, mode shift (e.g., to public transit), or large-scale production of novel alternative fuels. Specifically, we simulate the individual impacts of the following pathways:

- Sales of more fuel-efficient vehicles (e.g., best-in-class ICEV-G or hybrid electric vehicles (HEVs));
- Fuel consumption improvements from technological advances;
- Light-weighting of vehicles;
- Fleet downsizing;
- Compliance with eco-driving behaviors; and
- Reliance on mid-level ethanol blends, namely E15.

These pathways were selected as they directly impact the vehicle operation-phase emissions, which represent up to 90% of the total life cycle emissions of an ICEV-G [38]. We categorize them into three types:

1. Technological, for which the successful application is dependent on the attainment of a projected level of progress (e.g., lightweighting, performance, fueling infrastructure). Technological pathways are controlled by governments and manufacturers;
2. Decisional, relating to the vehicle purchasing choices of the consumers (i.e., drivers) themselves. The likelihood of selecting one choice over the other can vary with the socioeconomic characteristics of the end-user as well as the relative attractiveness of the option (i.e. perceived utility) [41]. In decisional pathways, governments

and manufacturers must actively increase the utility of the most fuel-efficient vehicle models;

3. Behavioral, relating to the drivers' conduct (e.g., driving practices). An effective behavior change can occur when the following three pillars exist: capability, opportunity and motivation [42]. Hence, a successful implementation of behavioral pathways depends on joint efforts between drivers and other stakeholders such as governments.

Due to the numerous cases arising from possible combinations of these pathways, we define six scenarios portraying different levels of commitment to the proposed pathways. Specifically, these include three scenarios with no electrification (the Conventional Road – with Shy (1), Steady (2) or Utopian progress (3)); two scenarios focused on hybrid electric vehicles (the New Conventional (4), and the New Conventional with Enhanced Progress (5)); and a fully electrified scenario for comparison (the Silver Bullet (6)). Scenario details are presented in section 2.3. The scenarios are not meant to be predictions of the future but instead, plausible, alternative visions (unless indicated otherwise) of how the transportation system may evolve in light of the application of some or all the proposed mitigation pathways or the absence thereof.

We complete a sensitivity analysis on the scenarios to understand the effects of a change in vehicle stock, survival rate, growth in travel demand and the effect of driving more efficient vehicles. We also apply a back-casting exercise on these scenarios to estimate the corresponding residual requirements on required fleet electrification levels to remain within emission budgets consistent with a 2 °C climate target as defined in section 2.4 and the resulting demands for lithium and electricity.

Further, by categorizing the proposed pathways into technological, decisional and behavioral, we put forth the distinctive roles various stakeholders can play (governments and manufacturers versus drivers/

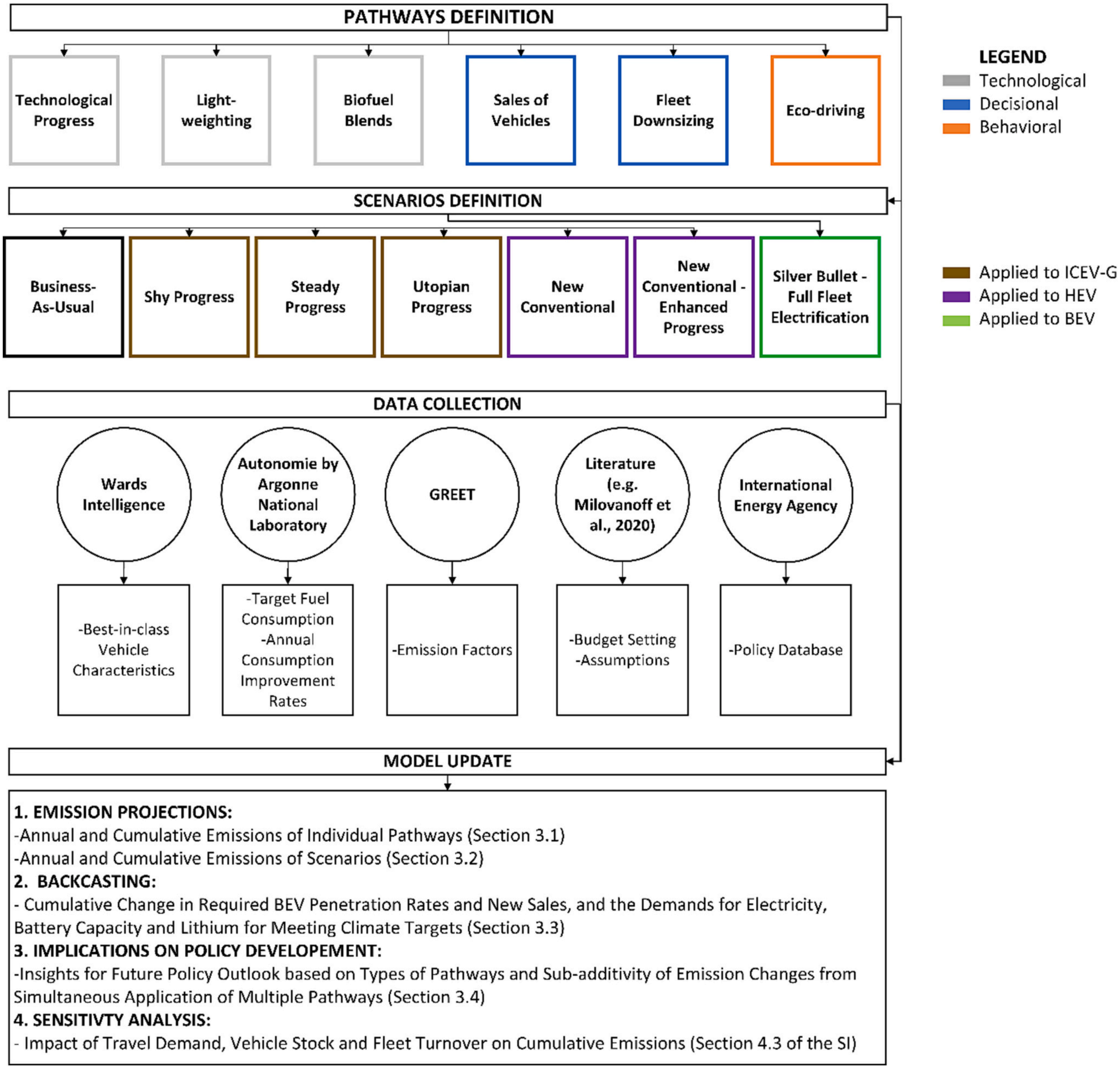


Fig. 1. Overview of inputs and results illustrating the logical structure of this article. Pathways represent individual technological, decisional or behavioral changes. Scenarios represent groupings of pathways at different levels of stringency, respectively focused on conventional, hybrid or battery electric vehicles. Data collection outlines key data inputs for this paper, which enter into the fleet LCA (FLAME) model update. Numbered headings at the bottom outline the organization of the results section.

owners) in the promotion and application of the proposed pathways. We then conduct a global review of policies promoting the suggested pathways and find that the proposed pathways could be transformed into policies based on precedence.

Fig. 1 provides an overview of the structure of this study. In the following sections, we describe the methods, data and assumptions with additional details in the Supporting Information (SI).

2.1. Modeling approach

The Fleet Life cycle Assessment and Material-flow Estimation (FLAME) Model was developed to help examine the GHG emission implications of large-scale deployment of mitigation strategies on the U.S. LDV fleet and is used in this study. Details of the modeling approach used in FLAME are provided by Milovanoff et al. (2019) [35]. FLAME consists of four modules:

1. The vehicle module that computes the vehicle characteristics (curb weight, material composition and fuel consumption) by vehicle size and technology;
2. The fleet module that projects the vehicle stock, travel demand and fuel use throughout the study period;
3. The material flow module that determines the demand from primary and secondary demand; and
4. The LCA module that estimates the fleet GHG emissions based on emission factors corresponding to different stages of the vehicle and fuel life cycles.

FLAME incorporates two vehicle sizes (cars and light trucks) and eight vehicle technologies. Inputs to the FLAME model were obtained from concurrent data from the VISION model [43], the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (GREET) developed by Argonne National Laboratory [44], and the Annual Energy Outlook (AEO) [45], among other relevant literature. A GitHub repository containing the FLAME model inputs and codes is available [46]. Section 2 of the SI elaborates on the FLAME inputs.

The FLAME model was modified for the purpose of this study to allow the simulation of pathways pertaining to best-in-class vehicle technologies, eco-driving, reliance on higher ethanol blends, larger market shares for HEVs and all improvements thereto. This version of the model is referred to as FLAME_2c.

2.2. Mitigation pathways assumptions and inputs

The following sections introduce key assumptions and inputs for each pathway. Table 1 provides a compilation of the distinguishing features of the simulated pathways (full details are provided in section 3 of the SI).

2.2.1. Fuel efficiency improvements from the sales of new vehicles

This pathway considers the impacts of the sales-weighted average fuel consumption of the new ICEV-Gs sold. We consider three cases: 1) A business-as-usual (BAU) sales mix in accordance with AEO's projections for market shares through 2050 [45], 2) a best-in-class (BIC) sales mix wherein the ICEV-Gs purchased as of 2021 are restricted to the best-in-class models, i.e., the models with the best fuel economy per vehicle class, 3) a sales mix characteristic of a shift from ICEV-Gs to HEVs by 2050, 2035 and 2021. HEVs in this work are powered by an internal combustion engine, which is assumed to be fueled with a gasoline/ethanol blend and an electric motor, which uses energy stored in a battery [49]. In FLAME, HEVs are distinguished from plug-in hybrid electric vehicles (PHEV), which require large batteries and an external source of electricity to charge the batteries [35].

We assume that the sales-weighted average fuel consumption of the new sales mix (ICEV-Gs or HEVs) sold represents the actual on-road fuel consumption of the various technologies (Additional information

Table 1

Summary of the cases evaluated per proposed mitigation pathway. Cases are categorized qualitatively as business-as-usual, best-in-class, low, moderate, high or extreme in terms of their levels of ambition. Improvements in fuel consumption due to technological progress and/or eco-driving are modeled with compounded annual rates, whereas improvements due to changes in market shares (size or fuel blend) are modeled with linearly increasing annual rates.

Pathway	Powertrain		Type	Cases Evaluated and used as Bounds for Fig. 2
	ICEV-G	HEV		
Sales of Vehicles (Fuel Efficiency Improvements)	√	√	Decisional	*Business-as-usual (BAU): New ICEV-G sales follow the BAU patterns from AEO [45] *Best-in-class (BIC): New ICEV-G sales are limited to the best-in-class models as of 2021 (Section 3.1.1. of the SI); *Hybrid electric vehicles (HEV-Year): HEVs replace new ICEV-G sales by 2050 (low), 2035 (moderate) or 2021 (high).
Technological Progress (Fuel Efficiency Improvements)	√	√	Technological	*BAU: Low fuel consumption improvements are projected for new vehicle models, in a manner that would be compliant with SAFE standards [47] *Low/High: Annual fuel consumption rates for the BAU, BIC, and HEV mixes are based on the most fuel-efficient projections from [48] for 2050 under low/high levels of technological progress (Section 3.1.2. of the SI) *Extreme: Fuel consumption improvement rates for the BIC ICEV-Gs sales mix follow the highest historical rates recorded for best-in-class models (Section 3.1.2. of the SI).
Lightweighting of Vehicles	√	√	Technological	*BAU: No lightweighting considered *Low: Steel intensive lightweighting (~4% weight reduction by 2035); *Moderate: Aluminum intensive lightweighting (~8% weight reduction by 2035); *High: Aluminum maximum lightweighting (~14% weight reduction by 2035) These cases were extracted from [35].
Fleet Downsizing	√	√	Decisional	*BAU: No downsizing; 60% of new sales are light trucks and 40%

(*continued on next page*)

Table 1 (*continued*)

Pathway	Powertrain		Type	Cases Evaluated and used as Bounds for Fig. 2
	ICEV-G	HEV		
				are cars through 2050. *Variable: The share of new light trucks sales is reduced to 40% by 2050 (low – trend reversal), 25% by 2050 (moderate), 0% by 2050 (high) and 0% by 2035 (extreme); *One Segment: Every vehicle in the fleet is downsized by one vehicle segment;
Eco-driving	√		Behavioral	*BAU: No eco-driving *Variable: The fleet fuel consumption is reduced by 3% by 2050 (low) and by up to 16% by 2050 (high);
Reliance on E15 Biofuel Blends	√	√	Technological	*BAU: E10 blends only *Variable: E15 blends amount to 30% of the fuel consumed by ICEV-Gs by 2050 (low), 100% by 2050 (moderate) and 100% by 2035 (high);

provided in section 2.3 of the SI). The on-road non-GHG emissions (e.g., particulate matter, NO_x) which were shown to vary based on the driving conditions and the powertrain [50] are outside of the scope of this study.

2.2.2. *Fuel efficiency improvements from technological Progress*

In the BAU case in FLAME, low fuel consumption improvements are projected for new vehicle models, in a manner that would be compliant with historical SAFE standards [47]. This pathway considers the impacts of the annual fuel consumption reductions of ICEV-G and HEV models resulting from technological progress. The fuel consumption values reported for the BAU, Best-in-Class and HEV sales mixes were subjected to different annual improvement rates for ICEV-Gs and HEVs compound over the study period, in accordance with a study conducted by Argonne National Laboratory [48] (Additional details provided in Section 3.1.2. of the SI). We calculate improvement rates based on the best projected fuel consumption rates in that study under low and high technological progress, so as to simulate aggressive reductions in emissions that can potentially be obtained from advances in ICEV-G powertrains. As an even more optimistic scenario, we simulate extreme improvements for ICEV-G fuel consumption based on the maximum historical improvement rates for best-in-class models. The details on how the different improvement rates were estimated and examples of specific technologies that would enable these improvements are presented in section 3.1.2. of the SI.

2.2.3. *Lightweighting of vehicles*

The vehicle module in FLAME includes an iterative model that estimates the vehicle curb weight resulting from a change in vehicle weight (primary savings), and the corresponding battery and powertrain resizing (secondary savings). Milovanoff et al. (2019) [35] used this feature of FLAME to examine the impact of light-weighting the U.S. LDV fleet. The authors evaluated three levels of lightweighting (steel intensive, aluminum intensive, and maximum lightweighting with aluminum), where changes in weight before and after lightweighting varied between 4% for steel intensive and 14% for the aluminum maximum light-weighting [35] (Additional information reported in the SI, section 3.2). This study applies these lightweighting cases to ICEV-Gs and HEVs and explores their impact as part of a more comprehensive set of mitigation strategies targeting the conventional gasoline fleet.

2.2.4. *Fleet downsizing*

The market share projections for the different powertrain configurations inputted into FLAME are based on AEO 2021 [45]. In this pathway, we simulate two types of downsizing applications targeting the conventional gasoline fleet: 1) Downsizing the fleet by one vehicle segment, i.e., switching all vehicles to a smaller one, for example from a midsize car to a compact car [51,52] and 2) shifting the new sales from the larger, heavier and less fuel-efficient light-truck models to the more fuel-efficient car models, while maintaining the same average size class within each of the two general categories (Additional information reported in the SI, section 3.3). For the purpose of this simulation, the market shares of other powertrain configurations (i.e., other than ICEV-G) were not altered.

2.2.5. *Compliance with eco-driving behaviors*

Eco-driving is the set of driving behaviors to reduce fuel consumption, such as gently accelerating and decelerating, maintaining steady speeds, trip planning, etc. [53–55] (A review of eco-driving and its impacts on fuel consumption is reported in Section 1.2 of the SI). This mitigation pathway simulates impacts from fuel consumption improvements obtained from properly imposed or incentivised and widely applied eco-driving practices. We model a maximum of 0.5% fuel consumption improvement per year, amounting to a compounded total of 16% after 30 years (well within ranges established from the literature review [56–60]– refer to Section 1.2 of the SI). We assumed fuel consumption improvements from eco-driving to be absolute in nature, meaning identical for all drivers, irrespective of the model year, age or size of the vehicle or the demographics of the drivers. Depending on the scenario, the same eco-driving rate was applied to ICEV-G cars and light-trucks as of 2020. A limitation of this analysis was the inability to account for the hidden interactions between the vehicle characteristics (performance and technology-related), operating mode (ecofriendly versus sports mode), fuel type and the driver demographics on the fuel consumption. Another limitation is the inability to predict the impact of eco-driving on a fleet level. Nevertheless, we assume our results provide an order of magnitude estimate of the potential effect of this strategy.

2.2.6. *Increased reliance on mid-level ethanol blends*

The mid-level ethanol blends pathway illustrates the impact of E15 blends (15% ethanol and 85% gasoline by volume), where ethanol is assumed to be mostly derived from corn in accordance with GREET 2021 [61] (the reference fuel blend in FLAME is E10). The scope of the work is limited to gasoline vehicles with no technological modification to accommodate other fuel types. Accordingly, ethanol blends exceeding E15 were excluded from the scope of analysis as these blends have not been certified for use in existing gasoline models in the U.S. (other than in flexible fuel vehicles). For this mitigation pathway, refueling stations were assumed to provide all needed volumes of E15 year-round. Further, underground storage tank systems were assumed compatible with the supply of E15 across the U.S. Fuel consumption values for E15 blends were adjusted to reflect the lower heating value and the increase in engine efficiency due to higher octane ratings [62]. The emission factors for this ethanol blend were derived from GREET [61]. Details on the modeling inputs and updates are included in section 3.4 of the SI. Further, the impacts of this pathway on ethanol demand are estimated in section 4.1 of the SI. Although other advanced drop-in fuels could offer much larger GHG reduction, they are outside of the scope of this study as the focus is on currently available options. While low carbon synthetic fuel (e-fuel) could be a promising option in the future, supply chains are currently limited and costly compared to other alternatives [63–66]. Nevertheless, we evaluate through a back-casting analysis the required gasoline life cycle carbon intensity compatible with the climate targets considered in this study under different future development scenarios.

By means of comparison, this assessment provides insights related to prospects of other fuels (e-fuels, biofuels, etc.) in the LDV sector.

2.3. Scenario definitions

The overall GHG implications of the proposed pathways will depend on the implementation date of each pathway as well as the corresponding rates of adoption. This leads to unlimited possibilities for

Table 2
Scenarios representing different levels of commitment to the pathways of the U.S. light-duty vehicle fleet from 2021 to 2050 evaluated in this study, in accordance with Table 2. The following abbreviations apply: BAU = Business-as-usual, ICEV-G = Gasoline internal combustion engine vehicle, LT = light-truck, E10 = fuel blends with 10% ethanol and 90% gasoline by volume, E15 = fuel blends with 15% ethanol and 85% gasoline by volume, AEO = Annual Energy Outlook.

		Technological Pathways			Decisional Pathways		Behavioral Pathways
Scenario	Description	Technological progress	Lightweighting of Vehicles	Reliance on E15 Biofuel Blends	Sales of Vehicles	Fleet Downsizing	Eco-driving
Business-As-Usual	New vehicle sales by technology and size follow AEO 2021 [45] projections in reference case, wherein conventional gasoline vehicles dominate sales and light trucks (LT) form ~60% of new sales through 2050. Low fuel consumption improvements are projected for new vehicle models, in a manner that would be compliant with SAFE standards. Reference fuel is E10.	BAU	BAU	BAU	BAU	BAU	BAU
Conventional Road - Shy Progress	New vehicle sales follow AEO projections in reference case. Fuel consumption of new models achieves estimates for best fuel-efficiency for low technological progress for ICEV-Gs by 2050 [48]. On-road fuel-consumption is enhanced due to a shy implementation of eco-driving practices. Steel-intensive lightweighting of ICEV-G fleet is implemented and trend in sales of LTs is reversed. E15 blends available year-round and form 30% of volume of fuel consumed by conventional gasoline vehicles by 2050. Remaining 70% of fuel consumed is E10.	Low	Low	Low	BAU	Low	Low
Conventional Road - Steady Progress	New ICEV-G sales limited to best-in-class models available and follow AEO projections in reference case. Fuel consumption of new ICEV-G models achieves best fuel-efficiency for high technological progress for ICEV-Gs by 2050 [48]. On-road fuel-consumption enhanced due to implementation of eco-driving practices. Maximum aluminum lightweighting of ICEV-G fleet is applied and 60% of ICEV-G LT sales are shifted to cars by 2050. E15 only blend available year-round in market by 2050.	High	High	Moderate	Best-in-class	Moderate	High
Conventional road - Utopian Progress	New ICEV-G sales are limited to best-in-class models and follow AEO projections in reference case. Fuel consumption of new models improves significantly and reaches all-time lows. On-road fuel-consumption enhanced due to implementation of eco-driving practices. Maximum aluminum lightweighting of ICEV-G fleet is applied and 100% of ICEV-G LT sales are shifted to cars by 2035. E15 completely replace reference E10 by 2035.	Extreme	High	High	Best-in-class	Extreme	High
New Conventional	By 2035, HEV salesreplace all ICEV-G sales. Low fuel consumption improvements are projected to new vehicle models, in manner that would be compliant with SAFE standards. No other mitigation pathways are adopted.	BAU	BAU	BAU	HEV - Moderate	BAU	BAU
New Conventional - Enhanced Progress	By 2035, HEV sales replace all ICEV-G sales. Fuel consumption of new HEV models achieve Autonomie estimates for high technological progress for 2050 [48]. Concurrently, maximum aluminum lightweighting is applied to HEV fleet by 2035 and 60% of HEV LT sales are shifted to cars. E15 completely replaces reference E10 by 2035.	High	High	High	HEV - Moderate	Moderate	BAU
Silver Bullet - Full Fleet Electrification	By 2035, BEV300 sales replace all conventional vehicle sales (gasoline, diesel, flexible fuel, hybrid, and natural gas).	BAU	BAU	BAU	6.5% annual increase in BEV sales	BAU	BAU

different simulations. For this reason, we defined six scenarios that represent different levels of commitment to the proposed pathways. The scenarios are not meant to be predictions of the future, but rather illustrations of how the LDV fleet may evolve through 2050 and what the resulting GHG impacts would be in comparison to the BAU scenario. There is no estimation of the likelihood of any scenario. The assessment seeks to quantify the cumulative GHG emissions from the proposed mitigation strategies in potential future developments and assess the uncertainty thereof. The time horizon of the scenario modeling is 2021–2050. The year 2020 is the last year for which most data on vehicle sales and characteristics were available at the time of writing, as detailed in Section 2 of the SI.

Table 2 provides a description of each scenario. The scenarios vary based on the type of powertrain considered, the mitigation pathways implemented as well as implementation speed and level of ambition for each mitigation pathway considered. The scenarios were defined to allow comparison between the BAU scenario and alternatives wherein 1) ICEV-G are dominant and become more efficient (Slow, Steady or Utopian Progress), 2) HEVs become dominant and are improved on (the New Conventional or the New Conventional - Enhanced) and 3) Full Fleet Electrification materializes by 2035. All the scenarios simulate an annual growth rate in vehicle kilometers travelled (VKT) of 0.8% [67]. The full fleet electrification scenario models a linear 6.6 annual percentage point increase in the share of BEV300 (i.e., BEVs with 300 mile range) out of the total LDV sales, leading to full fleet electrification by 2035. This scenario considers modest technological improvements to BEVs and relies on the AEO projections for the national electricity grid. Figs. SI-11 and SI-12 present, respectively, the changes in fuel consumption for ICEV-G and HEV for cars and light-trucks by scenario.

2.4. CO_2 emissions budget for U.S. light-duty vehicle fleet consistent with 2 °C climate target

We adopt a CO_2 emission budget of 34Gt CO_2 in this study. This budget represents the maximum cumulative CO_2 emissions that can be emitted by the U.S. LDV fleet from 2021 to 2050 to remain within the 2 °C global mean temperature change relative to pre-industrial levels by 2100. This budget is based on Milovanoff et al. (2020) who used the interpretations of the Global Change Assessment Model (GCAM) of the shared socio-economic pathways (SSP) [68]. The SSPs present various potential developments of societal components such as economic development, technological progress, population change, political stability, among others, which can mitigate or exacerbate climate change. Milovanoff et al. (2020) extracted from GCAM's interpretations of these SSPs data on the projections of the U.S. LDV stock through 2050, the direct and upstream CO_2 emission factors for the electricity grid and the emission factors for the direct combustion of fuels. The authors used this to obtain a life cycle budget for the U.S. LDV fleet for each SSP.

We adopt the most conservative emissions budget across all SSPs, corresponding to SSP 1 – 'Taking the Green Road'. This SSP reflects a future with high environmental consciousness, implying a great compliance with the sustainable development goals and leading to the lowest emission factors and LDV fleet projections across the SSPs. Of note, however, is that this approach still yields a relatively generous LDV sectoral carbon budget, reflecting the relative difficulty in decarbonizing the transportation sector. Other literature has considered more stringent LDV targets as discussed further in section 3.3.

We use this CO_2 budget (CO_2, not CO_2e) to benchmark the cumulative emissions from the pathways and scenarios evaluated in this study (in Gt CO_2eq and accounting for CO_2, CH_4 and N_2O emissions from the LDV sector). This introduces a minor inconsistency but ensures that we avoid burden shifting between different GHGs. We adhere to the use of a CO_2 budget (instead of a GHG emissions budget) as we recognize both from the literature [69] and from this study's results that CO_2 emissions are the predominant emissions across the lifecycle phases of all vehicle technologies. In effect, N_2O emissions contribute to <1% of the lifecycle climate change impacts of the average U.S.-based vehicle over 100 years. CH_4 emissions contribute to a maximum of 9% of the lifecycle climate change impacts of the average U.S.-based vehicle aggregated over 100 years. The maximum rate of 9% corresponds to a U.S.-based BEV300 where the largest contribution is traced to emissions from natural gas-powered electricity [69]. Further, while the linear response of warming to cumulative CO_2 emissions is well-established, the response to non-CO_2 emissions is complicated, given the shorter atmospheric lifetimes of these emissions compared to CO_2 and the resulting change in the ratio of CO_2 to total anthropogenic forcing [70]. In other terms, there is no scaling factor that can be applied to the CO_2 budget to account for non-CO_2 emissions that holds true for a range of scenarios [70].

2.5. Mapping of policies targeting internal combustion engine vehicles operating on conventional fuels

A variety of policies have been announced and applied globally to guide a resource-efficient and environmentally-conscious development of the LDV sector. We survey the policies compiled in the International Energy Agency (IEA) policy database [71] to determine the degree of prevalence of the approaches proposed in this study and the types of policies promoting them, if any, as a step to confirm their real-world applicability.

The IEA policy database includes 1262 transport policies compiled from various sources (e.g., IEA/IRENA Renewable Energy Policies and Measures Database and the IEA Energy Efficiency Database) from 1967 until present [71]. The database specifies the title, description, sector, jurisdiction (e.g., national, city), status (planned, in progress, ended), the type (e.g., standards, regulations, financial, educational), among others. The IEA policy database is not exhaustive of all transport policies worldwide, yet in our judgement it provides a representative sample thereof. We examine 775 policies covering road passenger transport (as tagged by the IEA) and categorize them by the pathways covered. (Additional details provided in Section 4.5 of the SI). The purpose of mapping these policies is to understand the prevalence and the overall applicability of the pathways examined in this study, not assess the appropriateness or outcomes of past policies.

3. Results

3.1. Individual pathways targeting the ICEV-G fleet can substantially reduce fleet lifecycle GHG emissions by 2050

The projected development of the U.S. LDV fleet following the BAU scenario will not meet the CO_2 emissions budget set for 2050. Our modeling shows that the cumulative emissions from the U.S. LDV sector from 2021 to 2050, hereafter referred to as **the cumulative emissions**, are roughly 49 Gt CO_2eq under BAU (i.e., 44% larger than the CO_2 emission budget of 34 Gt CO_2). The annual lifecycle emissions for 2021 for the U.S. LDV fleet were estimated at 1.5Gt CO_2eq, 30% higher than the tailpipe emissions reported by EPA for 2021 [72]. This is consistent with the share of tailpipe emissions out of the total lifecycle emissions (~71%) in FLAME. The annual emissions for 2050 are 1.8 Gt CO_2eq, a 26% increase from those in 2020 (as illustrated by Fig. 3). The BAU scenario is the reference case to which cumulative emissions from other mitigation pathways and scenarios are compared.

The impacts of the proposed pathways targeting the ICEV-G fleet on the cumulative emissions and annual 2050 emissions with respect to the BAU counterpart are summarized in Fig. 2. The order of pathways in the figure is based on the magnitude of cumulative GHG reductions estimated for each pathway. Substantial reductions could be obtained from some of the pathways targeting the conventional gasoline fleet. The simulated fuel consumption improvements due to technological progress applied to a fully hybrid electric sales mix or a best-in-class as of 2021 (BIC and HEV2021, respectively) led to the highest reductions in

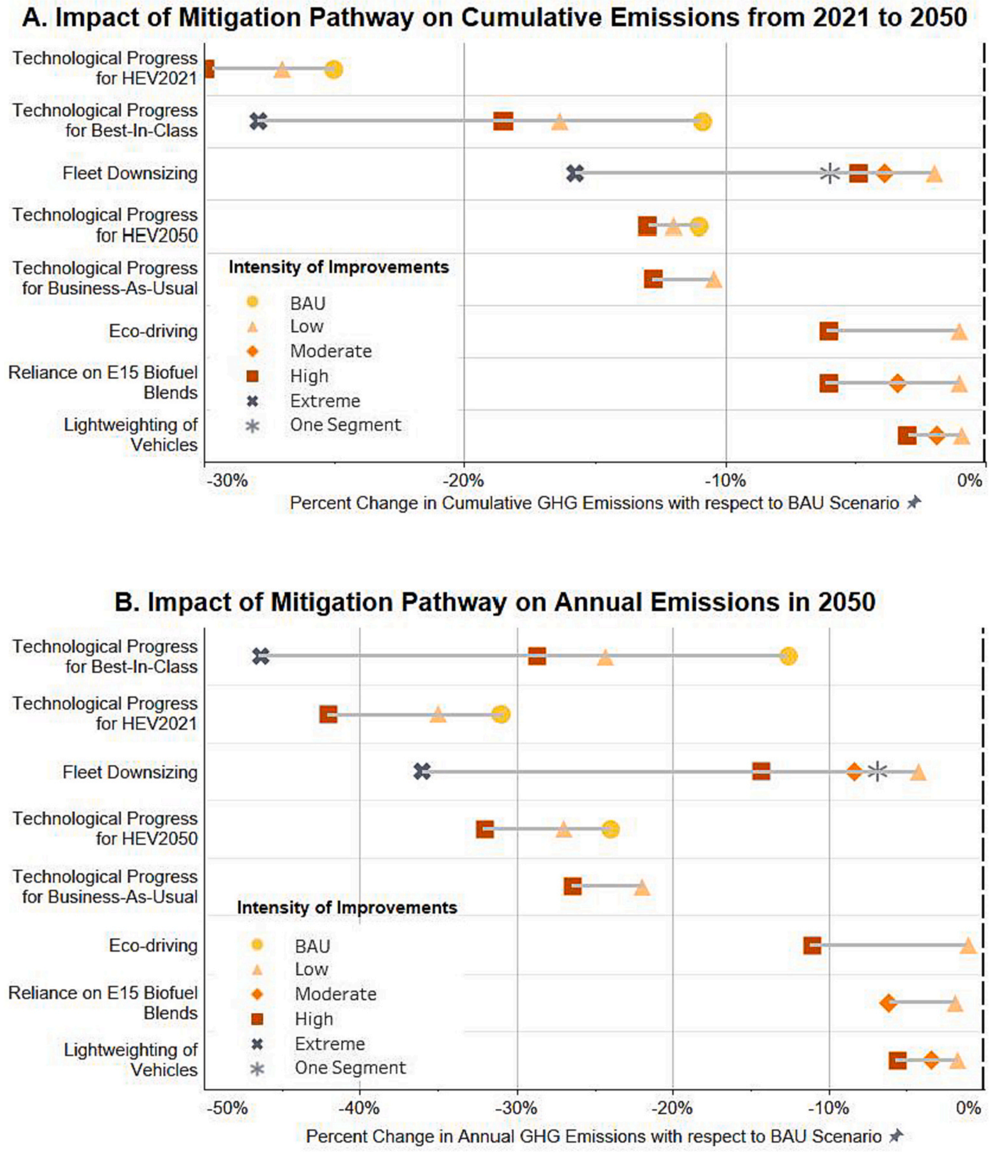


Fig. 2. Impact of proposed mitigation pathway on cumulative greenhouse gas emissions from U.S. light-duty vehicle fleet from 2021 to 2050 (A) and annual emissions in 2050 (B) with respect to the BAU case (49 Gt CO_2eq cumulative, and 1.8 Gt CO_2eq annual in 2050). The intensity of improvements of each proposed pathway are detailed in Table 1: Summary of the cases evaluated per proposed mitigation pathway. Cases are categorized qualitatively as business-as-usual, best-in-class, low, moderate, high or extreme in terms of their levels of ambition. Improvements in fuel consumption due to technological progress and/or eco-driving are modeled with compounded annual rates, whereas improvements due to changes in market shares (size or fuel blend) are modeled with linearly increasing annual rates.. The sales mix scenarios are shown merged with the technological progress scenarios. HEV2050/2021 refers to the case where HEVs replace new ICEV-G sales by 2050 (low) or 2021 (high). One segment refers to downsizing the vehicle by one vehicle segment and is only present in the “Fleet Downsizing” category.

cumulative emissions (25% to 30% for HEV2021 and 11% to 28% for BIC sales mix). Fleet downsizing also led to substantial reduction in cumulative emissions ranging from 2% to 16%. Other mitigation pathways such as eco-driving, reliance on E15 fuel blends and vehicle lightweighting led to more modest reductions in emissions (<6% each).

To put this into context, a 15% reduction in cumulative emissions from the U.S. LDV fleet from 2021 to 2050 translates to a reduction in emissions of about 7.4 Gt of CO_2, which is comparable to the total combined fossil CO_2 emissions from the USA and EU-27 countries in the year 2021 [73]. Importantly, these results indicate that such reduction in GHG emissions can be achieved with ICEV-Gs models where many of the technologies are already commercially available.

In effect, reversing the current trend in the sales of ICEV-G light trucks (as portrayed in the fleet downsizing, low) can reduce cumulative emissions by roughly 2%, whereas downsizing the fleet by one vehicle segment as of 2021 can reduce cumulative emissions by 6%. In contrast, limiting ICEV-G sales to the best-in-class models of 2020 (BIC with default rates for technological progress) can reduce cumulative emissions by roughly 11% whereas replacing new ICEV-G sales by their HEV counterparts by 2050 (HEV2050) could reduce cumulative emissions by 11%. The above strategies are mostly based on the vehicle buyers’ decisions, which could potentially be directed with appropriate incentives and policies.

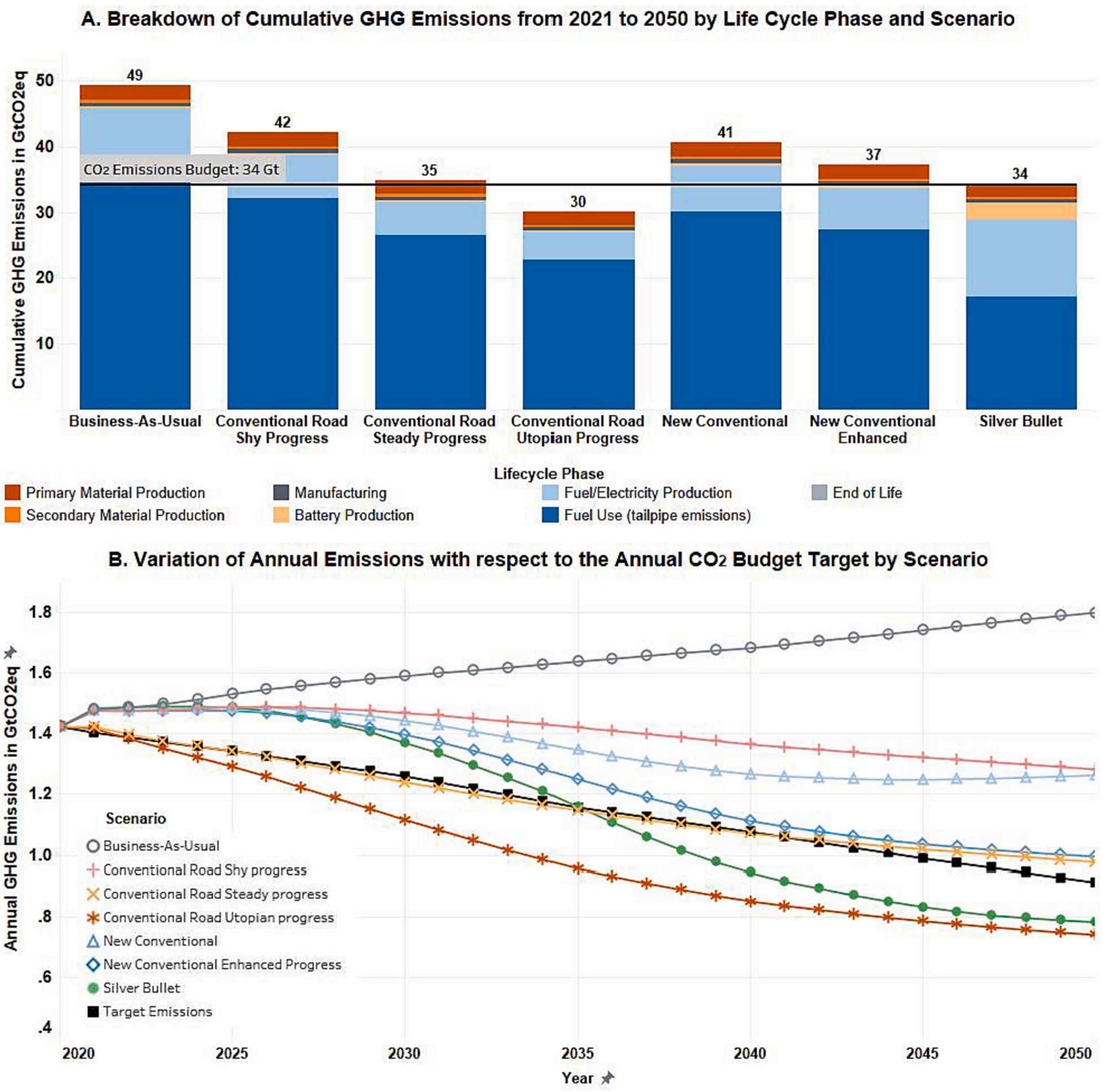
The impacts of the proposed pathways on the annual emissions in 2050 (Fig. 2 B) rank similarly to the impacts on the cumulative emissions, with the exception of the reductions introduced from the extreme technological progress to a best-in-class sales mix. Achieving the simulated extreme fuel efficiencies for this mix would cut annual emissions in 2050 by almost half (0.97 Gt CO_2eq) compared with the 2050 emissions in the BAU scenario. Even with such large improvements, the annual emissions would still be roughly 20% higher than the emissions that would be obtained if the new LDV sales were limited in full to BEV300 by 2035 (i.e., in the Full Fleet Electrification scenario shown in Fig. 3). This gap in annual emissions highlights why measures targeting internal combustion engine vehicles alone cannot be the only drivers to meet climate targets. However, they can serve as an important interim solution to narrow the mitigation gap until full electrification can be achieved.

3.2. Committed progress to the proposed strategies targeting ICEV-Gs could potentially close the GHG mitigation gap

Panel A of Fig. 3 compares the cumulative GHG emissions throughout the study period for the different scenarios (outlined in Table 2) broken down by life cycle activity with the cumulative CO_2 emissions budget for the U.S. LDV fleet. The figure shows there is an emission surplus of 15 Gt of CO_2eq between the projected cumulative emissions and the CO_2 emissions budget in the BAU scenario, referred to as the emissions gap.

Panel A highlights the substantial potential of some of the future development scenarios to meet climate targets. The Shy Progress simulates a slow implementation of achievable levels of the proposed pathways and reduces cumulative emissions to 2050 by roughly 14% compared to the BAU scenario, mitigating 45% of the emissions gap. The Steady Progress scenario assumes an immediate and aggressive advancement of the best-in-class mix along with associated high fuel consumption improvements. This bullish level of commitment can lead to the mitigation of almost 95% of the emissions gap. In contrast, the New Conventional scenario with Enhanced Progress, which stipulates that HEVs subjected to high fuel consumption improvements replace all ICEV-G by 2035, mitigates about 80% of the emission gap. However, larger reductions would be possible if the shift to a full HEV sales mix occurred before 2035, if the best-in-class HEV models were widely deployed, and/or if behavioral pathways, notably compliance with eco-driving, were applied and adopted.

Evidently, there is a limit to how much the conventional gasoline


A. Breakdown of Cumulative GHG Emissions from 2021 to 2050 by Life Cycle Phase and Scenario

B. Variation of Annual Emissions with respect to the Annual CO2 Budget Target by Scenario

Fig. 3. Cumulative and annual GHG emissions by scenario: Panel A shows the breakdown of cumulative GHG emissions from U.S. LDV from 2021 to 2050 by life cycle phase for scenarios. Of note, end of life emissions are low compared to other lifecycle emissions and thus do not appear on the figure. Panel B shows the variation of annual emissions with respect to the annual budget target by scenario. See section 3.3 for further discussion of more restrictive emission targets.

fleet can be decarbonized in the absence of massive breakthroughs in alternative fuels (e.g., e-fuels, which are outside of the scope of this study). This is delineated by the Conventional Road Utopian Progress scenario, which considers very optimistic, and likely unrealistic goals for each mitigation pathway, especially in terms of fuel consumption improvements from the technological advances. Under this scenario, the cumulative emissions are reduced from the BAU by roughly 40%, going slightly beyond the Silver Bullet (full electrification) scenario. The silver bullet scenario assumes aggressive EV penetration but does not otherwise assume large technological improvements. Cumulative emissions from the silver bullet scenario could drop even further, reaching as low as 26 Gt CO_2eq (not illustrated in Fig. 2) if EVs were powered exclusively by renewable sources from 2021 onward.

Notably, the substantial reductions in emissions across the scenarios result from improved fuel economy. This is shown in Fig. 3A where the largest portion of emissions is mitigated from the fuel production and use phases. In the silver bullet scenario, the fuel use phase is still a significant emissions source due to the ICEV-G stock remaining in the fleet during the transition to BEVs. This highlights that a deeper decarbonization of the LDV sector will require large-scale deployment of low-carbon fuels that can be used seamlessly in new and existing internal combustion engine vehicles to complement other mitigation measures for an accelerated decarbonization of the fleet.

Panel B of Fig. 3 illustrates the variation in annual emissions from 2021 through 2050 for the evaluated scenarios. The annual budget target as estimated from Milovanoff et al. (2020) is added in black (squares) [34]. Panel B shows that before 2035, only two scenarios (Conventional Road – Steady and Utopian Progress) are within the annual emissions budgets target. This is explained by the fact that most the ICEV-G strategies simulated in this study can be quickly adopted by the ICEV-G fleet, albeit at varying adoption rates. The wide and fast applicability of these strategies is an inherent advantage that could be leveraged for a quick mitigation of emissions from the LDV sector, signifying their characteristic as a bridging technology.

In contrast, the annual emissions from the simulated Silver Bullet scenario start higher than the annual budget and remain so until 2035. These elevated levels of annual emissions are attributed to the low market share of electric vehicles at the start of the study period and their higher embodied emissions, which require several years of operation before they are 'paid back' with lower operating emissions. It is clear however that the levels of emissions of this scenario become comparable to the most optimistic scenario around 2040. This is especially noteworthy as the Silver Bullet scenario simulates only mild improvements to the BEV fleet and the electric grid, compared to the extremely aggressive improvements simulated under the Conventional Road Utopian Progress. Faster than anticipated BEV efficiency improvements or grid decarbonization would further favour the Silver Bullet scenario. Specifically, the annual emissions in 2050 for the Silver Bullet scenario under a grid powered by renewable resources (not illustrated in Fig. 3) are estimated at 0.27 GtCO_2eq, a 60% reduction from even the lowest emission scenario currently in Fig. 3. Importantly, though, these scenarios do not have to be exclusive of each other. Although we modeled them as such, it is more likely that a cost-optimal policy strategy may require a portfolio solution that mixes and matches elements from the various scenarios simulated here.

We also perform a sensitivity analysis to understand the impact of the following factors on the cumulative GHG emissions from 2021 through 2050: 1) a change in the LDV stock resulting from variations in future oil prices, 2) growth in annual VKT, 3) drivers' reactions to vehicle efficiency improvements with respect to their VKT, known as the rebound effect, 4) a change in vehicle weight due to the inclusion of additional features and 5) implementation of vehicle lifespan caps. Section 4.3 of the SI details the methods and results. Notably, changes to the stock projections and to the VKT lead to the widest variability in cumulative emissions across the scenarios through 2050. The results also illustrated drivers' responsiveness to driving costs as larger fuel consumption improvements drove up cumulative emissions. The results showed the limited contribution vehicle lifespan caps can have toward meeting emission budgets when coupled with strategies focused on the conventional gasoline fleet. These were proven more effective when coupled with a strong push for electric vehicles (i.e., in the Silver Bullet Scenario). Annual increases in the vehicle weight due to the addition of new features resulted in mild changes to the cumulative emissions of ±1 Gt CO_2eq throughout the study period and the scenarios.

Beyond 2050 the annual life cycle emissions of an ICEV-G dominated fleet are unlikely to be reduced beyond the aggressive scenarios simulated here without a reduction in travel demand or further breakthroughs in alternative fuels. Effectively, without concurrent deployment of low-carbon fuels, strategies targeting conventional vehicles do not form long-term solutions as these vehicles still emit GHG emissions during their operation phase, whereas electric vehicles may generate little emissions during this phase if charged with renewable energy. Further, emission budgets are likely to become more stringent with time, as the net anthropogenic emissions continue to increase across all sectors and across all groups of GHG emissions [74], emphasizing the need for long-term solutions (i.e., greater push for fleet electrification and alternative fuels). However, interim measures targeting conventional vehicles can help delay exceeding the emissions budget, buying time for these deeper-decarbonization technologies to be widely deployed and for enabling infrastructures and clean energy materials to be suitably scaled-up.

3.3. Policies targeting ICEV-G can reduce the required fleet electrification rates

Recent analysis by the IEA revealed that a typical BEV requires as much as five times the critical materials used in a conventional car. Based on projected supply expansion, production could fall well short of the critical materials required by 2030 for a net-zero trajectory, with production deficits reaching up to 35% for lithium and 60% for nickel according to [75]. Thus, it is prudent for any decarbonization trajectory to also consider accessibility to key materials and enabling infrastructure to ensure a timely and organized transition.

We conduct a back-casting analysis to determine the levels of fleet electrification that would be required to remain within the 2 °C CO_2 emissions budget for 2050 under each of the scenarios (Fig. 4 Panel A, B and C). We assess the corresponding change in the electricity consumed in the use phase of the BEV fleet in year 2050 (Panel D) and the requirements for battery capacity (Panel E) and lithium used in the battery production of the BEV300 and HEV sales (Panel F). This analysis supposes Lithium-Ion (Li-Ion) batteries dominate the BEV300 and HEV battery market (the assumptions around the battery size and chemistry of the HEV and BEV300 deployed in the U.S. LDV fleet are detailed in Section 2 of the SI). We focus on lithium as an illustrative representative of the critical metals required as it is used in all Li-ion batteries and is projected to undergo production deficits: a recent study projected that the U.S. LDV fleet demand for lithium could be two-fold larger than the 2020 world lithium production by 2035 in a Silver Bullet scenario (assuming 100% BEV300 sales by 2035) [76].

Fig. 4 confirms that a 6.4% linear annual increase in the BEV penetration rate would be required to meet the 2050 budget based on the GCAM SSP1 results in the BAU, similar to what is modeled in the Silver Bullet Scenario. Over 400 million BEV would need to be sold, representing 100% of new sales after 15 years (i.e., by 2035). This is projected to consume 1600 TWh of electricity in 2050 (Panel D) and 25,000TWh throughout the study period (not illustrated in Fig. 4). To put this into context, the electricity consumed in the U.S. in 2021 across all sectors totaled 3900 TWh [77].

Results (Panels A and C) show that this BEV penetration growth rate can be reduced by a minimum of 24% if new ICEV-G sales are replaced by HEV counterparts, thus delaying the requirement for full fleet electrification by five years (i.e., until to 2040) (Reference to the New

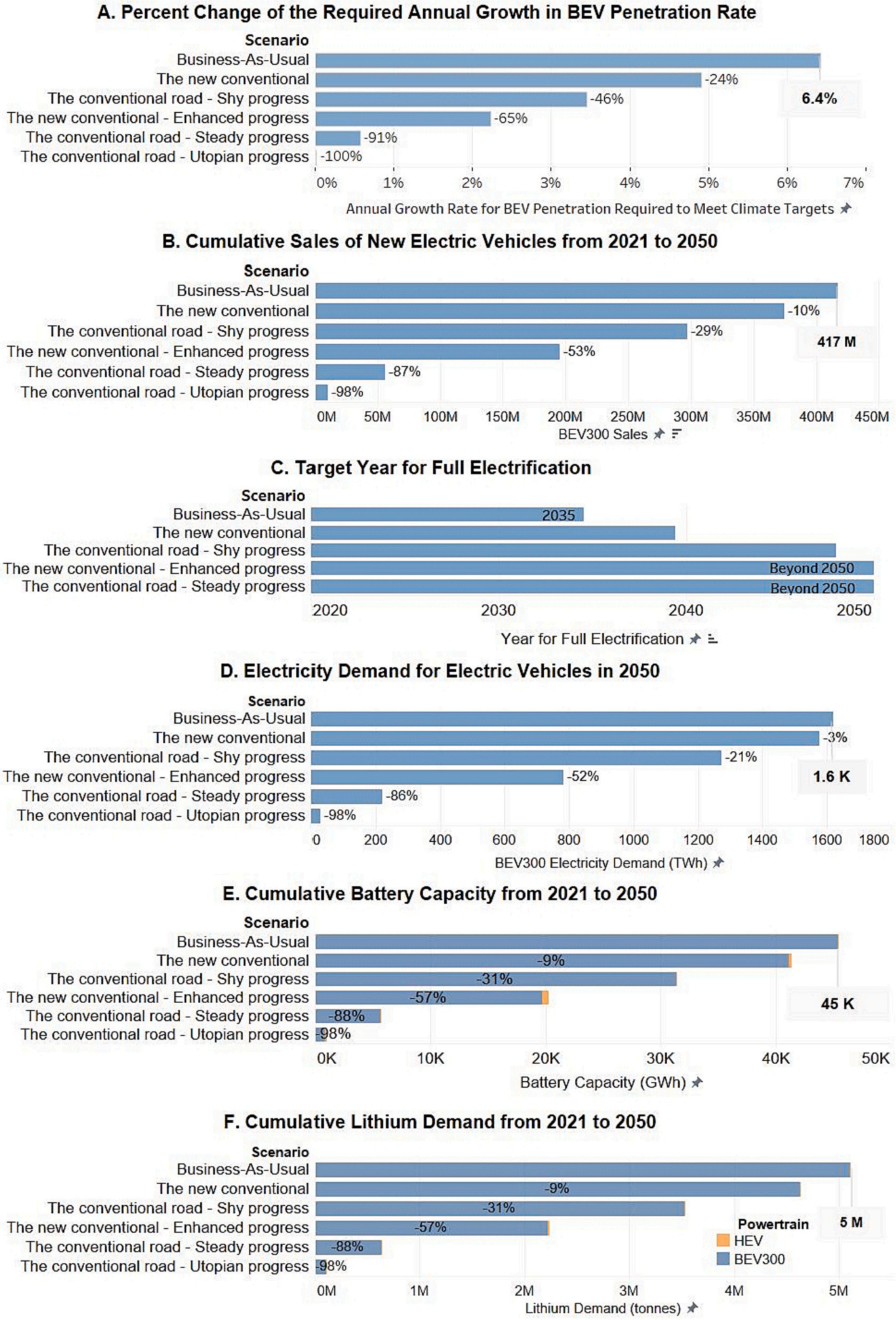


Fig. 4. Back-casting results illustrating the percent change in required annual growth in BEV penetration rate (A), drop in cumulative sales of new BEVs from 2021 to 2050 (B) and change in target year for full electrification (C), reduction in electricity demand for new electric vehicles in 2050 (D) and reduction in cumulative battery capacity and lithium demand for BEV300 (shown in blue) and for HEVs (in orange) from 2021 to 2050 (E and F, respectively) by Scenario. The scenarios are shown in a descending order determined by the required BEV sales as depicted in Panel A. The percentages in all the Panels indicate the rate of change from the value indicated for the BAU scenario, highlighted in boxes. In Panels E and F, the percentage corresponds to the reduction of the metric attributable to BEV300 only. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

conventional scenario) while still staying within the 2 °C CO_2 emissions budget. The rate can be further reduced (by a minimum of 46%) if policies compliant with the Shy Progress are implemented: this would delay the requirement for full fleet electrification by 13 years and reduce the BEV sales needed by a minimum of 29%.

Expectedly, a reduction in the sales of BEV300 translates into a reduced demand for electricity for the LDV sector in 2050 as demonstrated by Panel D. Depending on the scenario, the electricity consumption may be reduced by a minimum of 3% in the New Conventional Scenario, and by up to 98% in the Utopian Progress Scenario. Similarly, Panels E and D show a reduction in the required battery capacity and lithium demand attributable to the production of BEV300, ranging from a minimum of 9% in the New Conventional Scenario, and up to a maximum of 98% in the Utopian Progress Scenario. Panel F confirms that a future leveraging the benefits of HEVs containing Li-Ion batteries secures a 9% and 57% reduction in the lithium demand in the New Conventional and the New Conventional Enhanced Progress respectively. Of note, Nickel Metal Hydride (NiMH) batteries, which do not require lithium, are widely used at the present time for HEVs [47,48]. However, a shift to Li-Ion batteries for HEVs has been gaining momentum in recent years, as depicted in the Wards Intelligence dataset on the 2021 Model U.S. Specifications [78] where 80% of the new car models and 63% of the new light-truck models include Li-ion batteries.

Fig. 5 presents projections of the U.S. fleet stock technology composition in 2050 under each scenario in order to remain within the emission budget consistent with a 2 °C climate target for 2050. The figure demonstrates that short-term efforts for the LDV sector do not have to be restricted to one powertrain technology. Other factors such as total cost of ownership, critical materials demand, infrastructure availability, economic and technological outlooks should be considered when deciding on future strategies governing the sector.

A key limitation of this study is that we did not allow for large-scale penetration of novel alternative fuels. To illustrate their potential roles, we conduct a back-casting analysis to determine the required life cycle carbon intensity (CI) of gasoline deployed from 2021 to 2050 that would be sufficient to eliminate the emissions gap. The results in Table 3 show that the life cycle carbon intensity of gasoline in the BAU scenario would need to drop by 2 gCO_2eq/MJ every year, from 90 gCO_2eq/MJ in 2020 to 31 gCO_2eq/MJ by 2050 and have a weighted-average CI (by volume) of 58 g CO_2eq/MJ from 2021 through 2050. To put things into perspective, the rate of CI reduction per year (2 gCO_2eq/MJ extending to 2050) is 60% higher and extends longer than the rate required by California's Air Resources Board (CARB)'s Low Carbon Fuel Standard (1.25 gCO_2eq/MJ extending to 2030) to reduce the CI of transportation fuels by 20% in 2030, with respect to their 2010 levels [79]. As of 2023, the CI of certified pathways reported to/by CARB range from 7 to 77 gCO_2eq/MJ for ethanol and 21 to 63 gCO_2eq/MJ for renewable gasoline [79]. Expectedly, scenarios incorporating pathways targeting ICEV-Gs can afford more lenient life cycle carbon intensities for gasoline as evident in Table 3.

Table 3
Lifecycle Carbon Intensity of Drop-in Alternative Fuel required to remain within climate targets for each scenario. The Conventional Road – Utopian Progress Scenario and the Silver Bullet Scenario are not shown as their respective cumulative emissions through 2050 are within the CO_2 emissions budget adopted in this study.

	Gasoline Lifecycle Carbon Intensity (gCO_2eq/MJ)	
	Year 2050	2021–2050 Weighted Average (by Volume)
Business-As-Usual	31	58
Conventional Road - Shy Progress	50	70
Conventional Road - Steady Progress	87	89
Conventional road - Utopian Progress	90	90
New Conventional	59	74
New Conventional - Enhanced Progress	68	80

The results of this section vary with the CO_2 emission budget input into the back-casting analysis. Evidently, under tighter emission budgets, the emissions gap increases. Thus, to remain within the 2 °C carbon budget, higher penetration rates for electric vehicles powered by a lower GHG electric grid will be required. Alternatively, lower life cycle carbon intensities for gasoline will be needed.

Effectively, many emission budgets exist for the U.S. transport sector.

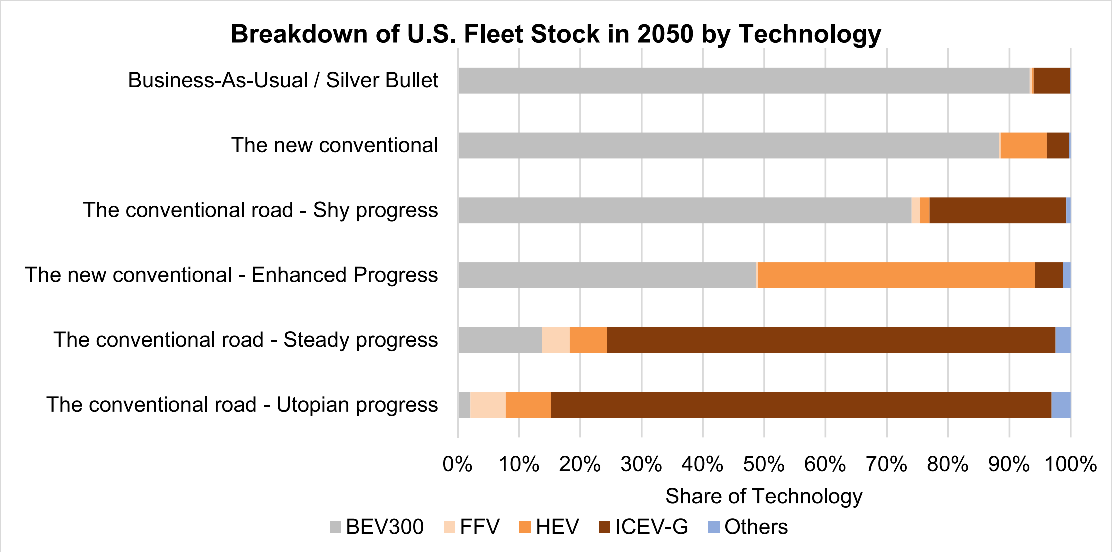


Fig. 5. Breakdown of U.S. light-duty vehicle fleet stock in 2050 by technology and by scenario. The scenarios follow the same order of Fig. 4; all include sufficient BEV300 penetration to be consistent with the assumed 2 °C emission target. The 'others' category includes and battery electric vehicles with ranges of 100 miles, plug-in-hybrid vehicles, diesel internal combustion engine vehicles, fuel-cell vehicles, and compressed natural gas vehicles. Note that in the BAU scenario, full fleet electrification is required by 2035 to remain within the emission budget consistent with a 2 °C climate target for 2050. This is consistent with the Silver Bullet scenario.

Authors have traditionally used a top-down approach to determine the emission budget for the entire U.S. Thereafter, authors have distributed this budget across economic sectors in equal proportion or in varying proportions to acknowledge higher mitigation costs for some of the sectors such as transport. Budgets for the U.S. LDV fleet for 2015–2050 range from 21.8 to 37.4 Gt CO_2 [34]. Recently, Zhu et al. (2021) adopted a 2021–2050 U.S. LDV cumulative emissions budget of 23.1 Gt CO_2eq to limit global warming to <2 °C [38]. This emission budget was based on the IPCC recommendation to remain within 70% of the U.S.'s 2010 LDV emissions by 2050 [38]. Though not directly comparable to our 2021–2050 target, it is evident that our 34 Gt CO_2 emission budget is generous compared to many others in the literature, suggesting there may be an even greater need to combine ICEV-G improvements with rapid BEV penetration than our model results indicate. The variability of the emission budgets for the U.S. LDV sector emphasizes the importance and need for appropriate allocation of the emission budget for future mitigation efforts.

3.4. A comprehensive and effective policy outlook would include diversified technological and behavioral pathways and would account for the sub-additivity thereof

This study offers two main insights on the selection process for effective mitigation pathways for the LDV fleet. First, an effective policy outlook would ideally include technological, decisional and behavioral pathways as defined in Section 2.2. To illustrate this, we breakdown in Fig. 6 the emission savings from the Conventional Road – Steady Progress Scenario by type of pathway. For the purpose of this section only, we simulate a null annual VKT growth rate in the Steady Progress Scenario from 2021 to 2050. While reducing travel demand is not a pathway covered in this study, we include it in this section as travel demand depends on drivers' behaviors and can greatly impact emissions. The addition of this pathway mitigated an additional 3.3Gt of CO_2eq compared to a Steady Progress Scenario accounting for the Business-As-Usual annual VKT growth rate of 0.8%.

Fig. 6 shows that the adoption of technological, behavioral and decisional pathways is essential to remain within the CO_2 emission budget. The mapping of the IEA policy database presented in Section 4.4 of the SI shows that governments have deployed a wide range of tools to target each of the pathways considered in this study (apart from a push for the sales of Best-in-Class models only). The dismissal of any type of pathway renders the goal of remaining within the climate targets unfeasible. This need for a combination of strategies would be even more pronounced under tighter emission budgets (see section 3.3). Drafting policies requires consideration of several criteria, namely efficacy, cost-effectiveness, feasibility, among others [80].

Second, selecting a set of pathways/policies based on the magnitude of GHG emissions reduction resulting from each pathway alone could be misleading. Emission reductions between a set of pathways may be 1) independent and are thus additive or 2) correlated and are thus sub-additive (implying redundancy between scenarios) or supra-additive (implying synergies between scenarios) [81].

Our results show that the total savings from the set of pathways particular to the modeled scenarios are smaller than the sum of the respective savings of the same set of pathways, as illustrated by Eq. 1.

Inequality on the sub-additivity of the savings in the cumulative

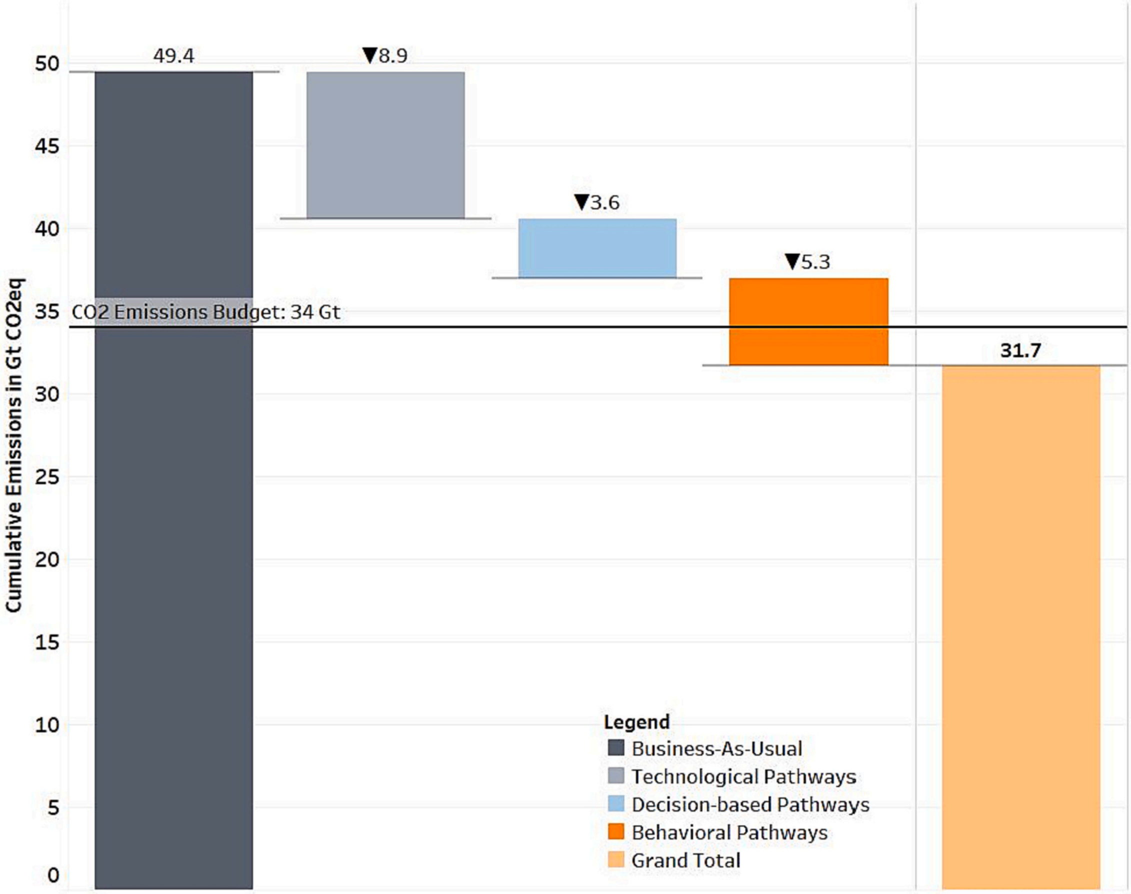


Fig. 6. Breakdown of the U.S. LDV cumulative emissions savings from 2021 through 2050 in the Conventional Road – Steady Progress Scenario (adjusted to account for 0% annual VKT growth rate) by type of pathway (technological, decisional and behavioral) with respect to the BAU Scenario). The 'Grand Total' column shows the cumulative (remaining) emissions of the fleet in the Steady Progress Scenario.

emissions

$$S\,(A \cup B \cup C\,) \leq S(A) + S(B) + S(C) \tag{1}$$

Where:

1. S is the cumulative savings in Gt CO_2eq from 2021 to 2050 with respect to the BAU scenario; and
2. A, B and C are mitigation pathways.

The additivity ratios for these correlated pathways were estimated using Eq. 2. A ratio of 0% would indicate perfectly additive strategies, while positive values indicate sub-additive strategies. Positive ratios equal to 7.2%, 16% and 20% were obtained in the Shy, Steady and Utopian Progress scenarios respectively, indicating redundant savings by the pathways.

Sub-additivity of mitigation pathways

$$Sub - additivity(\%) = 1 - \frac{Savings\ (A \cup B \cup C)}{Savings\ A + Savings\ B + Savings\ C} \tag{2}$$

Clearly, the sub-additivity of the impacts can be substantial in some cases, exceeding 10% of the projected reduction in emissions. Accordingly, we investigated further and determined the change in mitigation potential for seven combinations of the proposed pathways. Table 4 summarizes the results.

Table 4 shows that any evaluated combination is likely to lead to a positive sub-additivity percentage. The percentages reported range from 2% to a maximum of 37% for the combinations evaluated. Positive sub-additivity percentages for pathways targeting the LDV sector can be explained by the fact that the proposed pathways impact a common metric: fuel consumption. These sub-additivity percentages become particularly important when decisions on which strategies to adopt factor in projected emission reductions. One such example would be the estimation of abatement costs for various strategies, i.e., the cost to mitigate one unit of impact, such as one tonne of CO_2. The sub-additivity of mitigation strategies is an important concept that stretches well beyond the present study. Future work could target establishing average emission reductions per vehicle for the various policy combinations.

4. Discussion and conclusion

Widescale EV adoption is needed in the long run for deep decarbonization of the LDV sector, unless large modal shifts and low carbon fuels become realities. However, we show, using a U.S. focused case study, that there are complementary mitigation measures capable of moderating the required BEV penetration, at least in the short run, while still staying within the CO_2 emissions budget consistent with the 2 °C target through 2050. These mitigation strategies are interim measures that target conventional gasoline vehicles as a means to alleviate the challenges arising from an aggressive fleet electrification trajectory (i.e., surges in demand for critical materials and electricity consumption, infrastructure upgrades, among others), especially burdensome on low-income countries. Even with an aggressive electrification policy – like the proposed ICEV sales ban in several U.S. states - [82] new ICEVs will continue to be sold for over a decade globally and owing to the slow vehicle turnover rate, it will take even longer before ICEVs are completely retired from the LDV fleets. Thus, without breakthroughs in low-carbon fuels that can be readily dropped into existing vehicles, ICEVs are likely to dominate cumulative fleet GHG from now until 2050. Policies must therefore not ignore pathways to reduce emissions from gasoline vehicles.

This study confirms that depending on the level of technological progress and the policies enacted, promising LDV outlooks can include ICEV-Gs and/or HEVs in concert with an increasing reliance on BEVs. Specifically, an expeditious shift to a best-in-class ICEV-G sales mix or a fully hybrid electric sales mix, coupled with steady high fuel consumption improvements, will likely result in large reductions in cumulative emissions if the fleet continues to be dominated by conventional vehicles, as well as cumulative demand for critical materials. The analysis also identified limits for the ICEV-G fleet decarbonisation, suggesting that these measures can complement but not replace the need to develop alternative fuels and powertrains.

The validity of our results specific to the U.S. context is subject to the scope and model limitations (e.g. focus on ICEV-G and HEV only, no large-scale penetration of novel alternative fuels, no modeling of behavioral pathways for HEVs and BEVs, exclusion of environmental impacts beyond GHG emissions, exclusion of emissions from the production of HEV batteries and materials other than metals). The results also depend on key uncertainties related to emission budgets, heterogeneity within each technology and size class and between regions and consumers, fleet-based LCA, among others. Despite these limitations and uncertainties, the study provides insights to inform decisions and policies with respect to the LDV sector and meetings desired GHG

Table 4

Heat Map comparing the cumulative emissions savings from the combination of select levels of the mitigation pathways (detailed in column titled 'Cases Evaluated'). The diagonal in yellow shows the emissions savings in Gt CO_2eq corresponding to each individual case relative to BAU. The numbers reported above the diagonal correspond to the savings in emissions in Gt CO_2eq resulting from the combination of each pair of cases. A blue color scale is added to indicate the largest savings obtained (darker blue implying larger savings). The numbers reported below the diagonal show the sub-additivity percentage. An orange color scale is added to indicate the largest sub-additivity percentages obtained (darker orange implying higher sub-additivity percentages).

**The cases detailed in this table were applied to the ICEV-G stock only, i.e. for the purpose of this analysis, the improvements in technology, lightweighting, etc. were not applied to HEV stock. This may artificially increase the subadditivity ratio for the HEV cases.*

Pathway	Cases Evaluated*	Sales of Vehicles	Technological Progress	Lightweighting of Vehicles	Fleet Downsizing	Eco-driving	Reliance on Biofuels	Shift to HEV
Sales of Vehicles	**Best-in-Class**	**5.4**	**8.9**	**6.7**	**6.5**	**7.8**	**6.6**	**10.4**
Technological Progress	**High**	**24%**	**6.3**	**7.4**	**7.3**	**8.5**	**7.4**	**9.4**
Lightweighting of Vehicles	**High**	**2%**	**5%**	**1.5**	**3.1**	**4.2**	**2.9**	**8.7**
Fleet Downsizing	**Moderate**	**11%**	**11%**	**8%**	**1.9**	**4.6**	**3.3**	**9.9**
Eco-driving	**High**	**7%**	**9%**	**7%**	**7%**	**3.0**	**4.3**	**9.4**
Reliance on Biofuels	**Moderate**	**3%**	**4%**	**3%**	**3%**	**3%**	**1.5**	**9.8**
Shift to HEV	**High**	**26%**	**37%**	**13%**	**6%**	**19%**	**3%**	**8.6**

mitigation targets. Most importantly is the message that fleet electrification efforts need to be complemented by measures targeting conventional gasoline vehicles to ensure the timely decarbonization of the LDV fleets. Future work should investigate the GHG mitigation potential of other promising powertrains (e.g. plug-in hybrid, fuel cell electric vehicles, conventional ICEV powered by low carbon synthetic fuels) and potential changes in travel demand patterns or modes, in addition to policy recommendations and the associated environmental trade-offs across countries.

CRediT authorship contribution statement

Nadine Alzaghrini: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Alexandre Milovanoff:** Software, Methodology, Conceptualization. **Riddhiman Roy:** Visualization, Data curation. **Amir F.N. Abdul-Manan:** Writing – review & editing, Methodology, Funding acquisition. **Jon McKechnie:** Writing – review & editing, Project administration, Methodology, Funding acquisition. **I. Daniel Posen:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Heather L. MacLean:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author A. Abdul Manan is employed by Saudi Aramco. The research was funded in part by Saudi Aramco Technologies Company. The authors retained scientific independence in pursuing this work and no editorial control was exercised by the sponsor.

Data availability

Authors shared data sources and relevant information in the Supplementary Information Document.

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Appendix A. Supplementary data

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