Policies to retire old light-duty vehicles will help achieve California's zero-emissions targets and provide substantial air-pollution co-benefits.

Madalsa Singh[1*], Eleanor M. Hennessy[1,2], Sarah Saltzer[1,3], Andrew Berson[3,4], Inês M.L. Azevedo[1,5,6,7]

Affiliations:
[1]Department of Energy Science & Engineering, Stanford University
[2]School of Sustainable Engineering and Built Environment, Arizona State University
[3]Stanford Center for Carbon Storage, Stanford University
[4]Department of Management Science and Engineering, Stanford University
[5]Precourt Institute for Energy, Stanford University
[6]Woods Institute for the Environment, Stanford University
[7]Nova Business School, Portugal

[*]Corresponding author: madalsa@stanford.edu

Abstract: California has ambitious climate goals. The state aims to achieve economy-wide net zero emissions by 2045 and 100% zero-emissions vehicle sales by 2035. Decarbonizing transportation will be vital to achieving climate goals, as the sector is currently the state's largest source of greenhouse gas emissions. In this work, we develop a fleet turnover and retirement model for California's light-duty vehicle fleet. We simulate fleet characteristics, air emissions, and premature mortality under the following policy scenarios: (i) business-as-usual, (ii) zero-emissions vehicle sales mandates, and (iii) zero-emissions vehicle sales mandates combined with accelerated retirement policies. We test for policy stringency by considering different onset years (2025 to 2040) and vehicle retirement ages (10 and 15). Even with the current policy of selling only zero-emissions vehicles by 2035, 20% of the light-duty fleet in 2045 would still be powered by gasoline. Our work emphasizes the importance of retiring old vehicles. A policy mechanism that retires vehicles older than 15 years starting in 2025 would reduce cumulative CO_2 and premature mortality by more than 40 percent compared to business-as-usual between 2019 and 2045. Finally, a policy that provides an incentive of $6,000 for each retired vehicle starting in 2025 is cost-effective.

Introduction

California aims to achieve economy-wide net-zero emissions by 2045 [1]. Transportation is the state's largest source of climate-warming greenhouse gas (GHG) emissions, with light-duty vehicles (LDV) contributing to almost 120 million metric tons of CO_2 ($MtCO_2$) per year, representing 28% of the total emissions [2]. Air pollution from transportation also causes adverse health and environmental outcomes [3], [4], [5]. Fine particulate matter emissions, or $PM_{2.5}$ – particles with a diameter of 2.5 micrometers or less – are the most damaging from a health perspective. They can settle deep into the lungs and can cause lung cancer, cardiopulmonary diseases, and premature mortality [6]. Tailpipes of internal combustion engine vehicles (ICV) emit both primary $PM_{2.5}$ and precursor gases such as nitrogen oxides (NOx), volatile oxides (VOC), ammonia, and small amounts of sulfur oxide (SO_2). Precursor gases undergo further atmospheric reactions to form secondary $PM_{2.5}$ [7]. A rapid overhaul of the LDV fleet, moving from conventional vehicles to zero-emission vehicles (ZEV), will be essential to achieve the state's climate and public health goals [8], [9].

California has primarily used sales targets and financial incentives to increase ZEV adoption. The 2022 Advanced Clean Cars II regulations strengthen vehicle emissions standards and aim to increase ZEV sales to 100% by 2035 [10]. The state also provides various financial incentives to spur ZEV adoption. For example, until 2023, the Clean Vehicle Rebate Project offered rebates from $1,000 to $7,500 to purchase or lease a new ZEV in California [11]. In addition, ZEV owners receive tax credits, rebates for used ZEVs, lane exemptions, and toll discounts [12]. We summarize other federal and state financial incentives for ZEV adoption as of 2024 in SI Section 1.

Despite policies to spur ZEV adoption, achieving fleet-wide decarbonization of LDV fleet will require additional policies to remove internal combustion vehicles (ICVs). A typical passenger car lasts between 20 and 25 years [13]; lately, consumers have kept their vehicles longer [14]. Even if California achieves its 2035 sales target, some ICVs sold until then will remain in the fleet until 2045. These remaining vehicles will need to be removed before their natural lifetime. Retiring older vehicles in California will also provide substantial co-benefit of reduced air pollution. In 2019, 77% of LDV NOx in California was emitted by vehicles 15 years old or older [15]. NOx is a collective term for a mixture of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), and it is the largest source of overall $PM_{2.5}$ from vehicles [16], [17]. Additionally, pollution from older vehicles disproportionately impacts the state's Latino, Black, and low-income communities [6]. Accelerated retirement policies can achieve triple wins by reducing carbon emissions while improving air quality and exposure equity.

In the United States, accelerated vehicle retirements have been previously used as part of the portfolio to reduce transportation emissions. For example, in 2009, the Car Allowance Rebate System (or “Cash for Clunkers”) program incentivized households to trade less efficient vehicles for more efficient ones. The program cost $2.8 billion and retired ~677,000 cars ($4,135 per vehicle) [18]. Similar programs have existed in California. For example, the Clean Cars 4 All program incentivizes low-income people to replace an old polluting vehicle with a ZEV and other clean mobility options [13]. The program has spent $105 million to replace 13,000 vehicles ($8,076 per vehicle) [19]. In California, the Bay Area Air Quality Management District’s Vehicle Buy Back program and Consumer Assistance Program’s vehicle retirement program provide vehicle owners between $1,000 - $1,500 to retire their older, polluting vehicles [20], [21].

Here, we assess the implications of different transportation policy mechanisms, such as ZEV mandates and accelerated retirements, on fleet characteristics, air emissions, and premature mortality. We use a fleet turnover and retirement model benchmarked to projections of the California Air Resources Board (CARB), the state’s air emissions regulator. Fleet turnover models have been extensively used in the literature to evaluate transport emissions, policy implications of fuel economy, tax credits, light-weighting, vehicle ownership, and miles driven [22], [23], [24], [25], [26], [27]. In the rest of this paper, we start by outlining our methods and data, followed by our results and conclusions.

Data and Methods

In this work, we develop a fleet turnover and retirement model and consider the following scenarios: (i) business-as-usual, (ii) scenarios that incorporate ZEV sales mandates, and (ii) ZEV sales mandates combined with a policy mechanism that requires accelerated retirements. We consider two ZEV mandate years (2035 and 2040) and test the effect of accelerated retirement policy stringency by considering different onset years (from 2025 to 2040) and the vehicles' retirement age (10 and 15 years). We estimate each scenario's annual and cumulative greenhouse gas emissions, criteria air pollutants, and $PM_{2.5}$-related premature mortality. We perform a simple cost-benefit analysis to compare different scenarios.

We use the following modeling approach. First, we characterize the 2019 LDV fleet and its air emissions using CARB’s fleet and emissions database (EMFAC) [15]. EMFAC includes estimates of the number and the characteristics of vehicles registered in California, as well as projections of sales, emissions, vehicle miles traveled (VMT), and stock of vehicles until 2045. Second, we develop a fleet turnover model until 2045 whose characteristics match CARB’s business-as-usual scenario. Third, we simulate the effects of ZEV mandates and accelerated retirements and estimate annual tailpipe and electricity generation air emissions from vehicle fleets for various scenarios between 2019 and 2045. Then, we value health and climate change externalities associated with each scenario’s emissions. Finally, we estimate the cost-effectiveness of different accelerated retirement scenarios. Below, we provide more details regarding our data and methods.

Characterizing the 2019 LDV fleet and its emissions. We use CARB’s EMFAC (version 2021) data and projections. EMFAC includes historical data and future fleet projections of LDV emissions by age and vehicle type [15]. EMFAC’s emissions database has historical data on vehicle stock by fuel and vehicle type, VMT, CO_2, and criteria air pollutant emissions. In Table 1, we provide some key figures for the calendar year 2019 fleet and emissions, along with the contribution of vehicles that are 15 years old or older (pre-2004 models). Comprehensive vehicle counts by age (vintage) are provided in SI section 2A.

Table 1: Vehicle stock, vehicle miles traveled (VMT), air emissions from the 2019 LDV stock, and the proportion attributable to vehicles older than 15 years. Data from CARB EMFAC for the calendar year 2019 [15].

	Fleet-wide vehicle characteristics				Proportion due to vehicles >15 years as of 2019 (pre 2004 models)			
	Stock (millions)	VMT (billions)	CO_2 emissions (10^6 metric ton)	NOx emissions (10^3 metric ton)	Stock	VMT	CO_2	NOx
Passenger Cars	14.36	185	57.15	21.50	18%	10%	12%	65%
Light Duty Trucks 1	1.57	17	6.35	6.12	47%	33%	37%	91%
Light Duty Trucks 2	5.83	75	30	15.7	19%	13%	16%	79%
Med. Duty Trucks	4.38	52	25.4	16.5	26%	18%	20%	85%
Total	26	330	119.75	59.87	21%	13%	16%	77%

Modeling the fleet turnover. EMFAC also contains future projections on vehicle stock, emissions, and VMT under a business-as-usual scenario. We benchmark our stock and flow model to the business-as-usual projections used by CARB (SI Section 3). Our stock and flow model estimates the annual vehicle stock characteristics by age, vehicle type, and fuel type as follows:

$$Q_{t+1,m,v,f} = Q_{t,m,v,f} - R_{t,m,v,f} + S_{t,m,v,f}$$

where t represents the year, m represents the vehicle model year, v represents vehicle type (passenger vehicle, light duty trucks 1, light duty trucks 2, medium duty trucks[1]), and f represents the fuel type (gasoline, electric, hybrid, natural gas, or fuel cell). $Q_{t+1,m,v,f}$ and $Q_{t,m,v,f}$ are the stock of vehicles by vehicle and fuel type in year $t+1$ and year t, respectively. $R_{t,m,v,f}$ is the number of vehicles naturally retired during year t, and $S_{t,m,v,f}$ is the number of vehicles sold in year t. The total stock of vehicles and sales in each year is maintained the same across all scenarios. Natural retirements are determined using survival profiles using EMFAC data, which specify the percentage of vehicles of a given vehicle type that survive to a specified age (see the SI section 2B for survival profiles used in this work).

Policy intervention. We model two policy interventions: (i) ZEV sales mandates and (ii) ZEV sales mandates combined with accelerated retirements.

> *(i) ZEV sales mandate scenarios.* We assume that when sales mandates for ZEVs are in place, sales linearly increase to 100% between 2019 and the year the mandate kicks in, and the relative distribution of other fuel types remains the same as under the BAU scenario. We assume that all new vehicle sales are ZEV after the mandate year. For simplicity, we assume that ZEV sales are electric vehicles, but the model can specify a split between hydrogen and electric vehicles (SI section 2C).
>
> *(ii) Accelerated retirement scenarios*. We simulate policies with early retirements as follows:
>
> $$Q_{t+1,m,v,f} = Q_{t,m,v,f} - R_{t,m,v,f} - Y_{y,t,m,v,f} + S_{t,m,v,f}$$
>
> $Y_{y,t,m,v,f}$ represents the number of vehicles in the stock of age y or higher, vehicles of type v, fuel type f, and model year m in year t. The number of early retirements is determined by the year the policy takes effect t_r, and the minimum age of vehicles to be retired a_r. All ICVs at retirement age or older are retired from the fleet in the retirement year as well as in all subsequent years:
>
> $$Y_{y,t,a,v,f} = Q_{t,a\geq a_r,v,f}$$
>
> $$\forall \mathrm{t} \geq \mathrm{t_r}, \mathrm{f} \in \{\text{Diesel, Gasoline, Natural Gas}\}$$
>
> We assume early retirements are substituted with new ZEV.

Vehicle miles driven assumptions, fuel consumption, and emissions. We assume that the total VMT driven by all vehicles in the fleet across all scenarios is the same as under the BAU scenario. Under the BAU scenario, vehicles are driven less as they age. For scenarios with accelerated retirements – which changes the age composition of the fleet compared to BAU -- we scale each scenario's VMT to ensure it remains the same as BAU VMT. More details on VMT calculation are provided in the SI section 2D.

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[1] Light-duty vehicles are divided into passenger cars (smaller vehicles such as sedans), light-duty trucks 1 (vehicles with gross vehicle weight rating below 6000 lbs. and equivalent test weight below 3750 lbs.), light-duty trucks 2 (vehicles with gross vehicle weight rating below 6000 lbs. and equivalent test weight between 3751 and 5750 lbs.), and medium-duty trucks (gross vehicle weight rating between 6000 and 8500 lbs.).

We estimate fuel consumption using VMT and fuel economy as:

$$FC_{t,m,v,f} = \frac{VMT_{t,m,v,f}}{FE_{m,v,f}} \cdot Q_{t,m,v,f}$$

Where *FC* is fuel consumption (measured in gallons of gasoline, gallons of diesel, or gasoline gallon equivalent, or electricity consumption in kWh), *FE* is fuel economy (mpg or mpge), and we use indicators for model year (age) m, vehicle type v, and fuel type f in year *t*. SI section 2E provides EMFAC-derived historical and future fuel economy assumptions.

We estimate ICV tailpipe emissions by multiplying fuel consumption by fuel emissions factors (8.60 $kgCO_2$/gallon for gasoline, 10.15 $kgCO_2$/gallon for diesel, and 6.55 $kgCO_2$/gallon gasoline-equivalent for natural gas) [15]. For electric vehicles, we assume California's grid average carbon intensity in 2019 is 299 gCO_2/kWh [28], and it decreases linearly between 2019 and 2045 to meet the state mandate of zero-carbon electricity by 2045.

Air quality and health impacts modeling. We estimate the county-level emissions of primary $PM_{2.5}$ as well as precursor pollutants of nitrogen oxides (NO_X), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and ammonia (NH_3) for vehicles in the BAU and in each of the scenarios. We calculate criteria pollutant emissions factors (g pollutant per gallon) by vehicle age using EMFAC data and then multiply fuel consumption estimated in the previous section for each vehicle type, model year, and fuel type. More details on model year-specific EMFAC-derived emissions factors for pollutants are provided in SI section 2F. ICV tailpipes contribute to both primary $PM_{2.5}$ and secondary $PM_{2.5}$ formed due to the atmospheric reactions between precursor pollutants such as NOx, VOC, SO_2, and NH_3.

For emissions of air pollutants from electric vehicle charging, we follow the same methods as in our previous work [29]. In brief, we assume all battery electric vehicles sold from 2019 to 2045 have an increasing fuel efficiency (SI section 2E) and the same lifetime and survival probability as a conventional vehicle. We ignore battery degradation but account for VMT decrease with age. We estimate the criteria air pollutant emissions associated with total electricity generation in the Western Electricity Coordinating Council (WECC). Renewable electricity generation has no associated air pollution. We then allocate the increase in electricity generation from ZEV charging to all power plants in proportion to their current annual generation and find the increase in emissions of $PM_{2.5}$, SO_2, VOC, and NO_x, as well as secondary $PM_{2.5}$ formed due to atmospheric reactions of these gases.

We use a reduced-complexity air quality model, InMAP, to estimate the annual average change in $PM_{2.5}$ concentration given the annual emissions of criteria pollutants. The InMAP Source Receptor Matrix (ISRM) maps county-level emissions to changes in $PM_{2.5}$ concentrations on a variable grid. The grid-cell size in InMAP varies from 1 km × 1 km (typically in urban areas) to 48 km × 48 km (typically in rural areas), depending on the population density gradient and pollutant concentrations. More details on InMAP, ISRM, and data processing are provided in the cited studies [29], [30], [31], [32], [33]. We then estimate the premature mortality due to the change in $PM_{2.5}$ for each scenario in each grid cell using a dose-response function as follows:

$$\Delta M_x = M_x^0 \left(e^{\frac{\ln(\beta)}{10} \Delta PM2.5} - 1 \right) \cdot Pop_x$$

Where ΔM_x is the change in premature mortality, M_x^0 is the baseline all-cause mortality rate, β is the hazard ratio associated with exposure to an additional 10 $\mu g/m^3$ of $PM_{2.5}$, and Pop_x is the population in the grid. We use Krewski et al.'s hazard ratio of 1.06 [34].

The analysis so far provides us $PM_{2.5}$ concentration and associated premature mortality for the 2019 LDV fleet and 2019 power plants in WECC. To find cumulative premature mortality for different scenarios between 2019 and 2045, we scale the 2019 $PM_{2.5}$ using annual NOx emissions (for ICVs) and annual electricity requirement for charging (for ZEVs) as factors.

For ICVs, we scale the 2019 LDV $PM_{2.5}$ by annual NOx emissions of each year and scenario as given in the equation below.

$$PM_{2.5\ ICV\ v,s,t,x} = PM_{2.5\ LDV,v,2019,x} \cdot \frac{NOx_{ICV\ v,s,t}}{NOx_{ICV\ v,2019}}$$

$PM_{2.5v,s,y,x}$ is the increase in $PM_{2.5}$ concentration in grid cell x in scenario s in year t caused by vehicle type v. $PM_{2.5\ LDV,\ v,2019,x}$ is the increase in $PM_{2.5}$ concentration in the same grid cell due to 2019 LDV fleet. $NO_{XICV,v,s,y}$ represents the statewide NO_X emissions caused by vehicle type v in scenario s in year t, and $NO_{XICV,v,2019}$ is the NO_X emissions caused by vehicle type v in 2019. We use NO_X emissions as our scaling factor as they are the largest contributor to the increase in $PM_{2.5}$ concentrations for ICV [16].

For EVs, we scale the $PM_{2.5}$ concentration from the WECC power plants in 2019 by annual electricity consumption due to electrification for each scenario. We also include a year-specific emissions reduction percentage, P_t, to reflect a reduction in the air emissions from power plants to achieve the state mandate to achieve zero-carbon electricity by 2045. This simplification is justified since the relationship between emissions and concentration is held via a source-receptor matrix, and changes in $PM_{2.5}$ concentration due to declining emissions of criteria air pollutants will continue to hold for years between 2019 and 2045.

$$PM_{2.5\ ZEV\ \ v,s,y,x} = PM_{2.5\ WECC,2019,x} \cdot \frac{Electricity\ required\ for\ charging_{\ v,s,y}}{Electricity\ Generation_{WECC,2019}} \ .P_t$$

For calculating cumulative premature mortality, we also assume that the VMT and vehicle population distribution in counties were constant between 2019 and 2045.

Cost-benefit of policy interventions. Implementing a large, accelerated retirement program for older vehicles will require a financial incentive for vehicle owners. For illustration, we simulate the costs of accelerated retirement policies where each vehicle retired before lifetime receives $6,000. We assume a social cost of carbon (for avoided CO_2) of $190/metric ton (in 2020$) for the benefits of avoided CO_2 emissions [35], [36]. We further assume that avoided premature mortality associated with reducing criteria air pollutant emissions is valued at the value of statistical life of roughly $10 million, which is aligned with current agency values [37], [38]. We represent the cumulative costs and benefits across scenarios in terms of net present values using a discount rate of 7%.

Results

The 2035 ZEV sales mandate will lead to significant CO_2 emissions reductions. In Figure 1, we show annual vehicle stock and CO_2 emissions by fuel type for the BAU scenario and the scenario where 100% of the vehicles sold by 2035 are ZEVs.

Under BAU, vehicle fuel economy improvements will lead to a 23% decrease in CO_2 emissions by 2045 compared to 2019. In comparison, successful implementation of the 2035 ZEV sales will lead to CO_2 emissions reductions of 90% by 2045 when compared to 2019 levels. Cumulative CO_2 emissions between 2019 and 2045 under the BAU scenario would amount to 2.8 $GtCO_2$, whereas under the ZEV 2035 mandate, cumulative CO_2 emissions total roughly 1.95 $GtCO_2$ (Figure 4). Thus, implementing the 2035 ZEV sales mandate will total 0.85 $GtCO_2$ cumulative avoided emissions between 2019 and 2045.

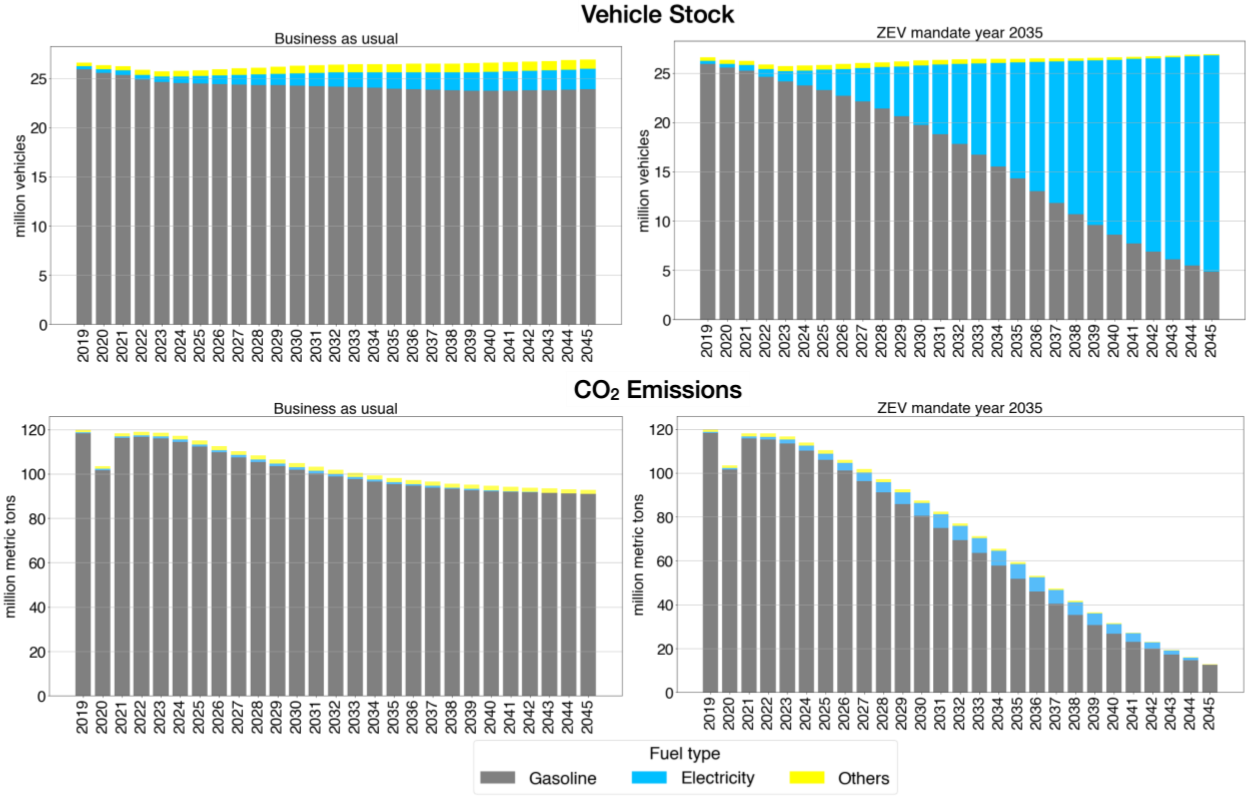


Figure 1: Vehicle stock and CO_2 emissions by fuel type and emissions under the BAU and 2035 ZEV mandate scenario.

Accelerated retirements will be required to achieve zero carbon emissions in the light-duty sector by 2045 in California. Although ZEV mandates provide significant emissions reductions, they are insufficient to achieve zero emissions by 2045. Even if California achieves 100% ZEV sales by 2025 – an unlikely feat – there would still be roughly 2.5 million ICVs on the road by 2045, contributing to at least 5 million metric tons in annual CO_2 emissions. Maintaining the 2035 ZEV mandate or delaying it to 2040 results in 20-30% of the 2045 LDV fleet being powered by gasoline (Figure 2a). These remaining ICVs will emit at least 10-17% of the 2019 LDV CO_2 emissions. The estimates can be higher if vehicles are retained for longer or driven more over their lifetime (Figure 3a).

To ensure the LDV fleet reaches zero emissions by 2045, we test an additional policy mechanism of accelerated retirement of older ICVs. We assume these retired vehicles are replaced with new ZEVs. In panel B of Figures 2 and 3, we show the effect of accelerated retirement in addition to the 2035 ZEV sales mandate, i.e., 100% of new vehicle sales will be ZEV by 2035 as per current California policies. We then test the effect of retiring and replacing vehicles 10- or 15 years and older, starting in 2025, 2030, 2035, and 2040.

We find that retiring vehicles 15 years or older, in addition to the 2035 ZEV mandate, gets us very close, but not to complete zero emissions. The residual emissions in 2045 for accelerated retirement of vehicles over 15 years could range between 1.6% (retirement starts in 2025) to 2.1% (retirement starts in 2040) of 2019 LDV emissions. To achieve zero emissions by 2045, which we define as residual emissions being less than 1% of 2019 emissions, the state will need to retire vehicles 13 years and older starting in 2025. SI section 4 provides fleet evolution and emissions curves for vehicle retirement ages 11, 12, 13, and 14 starting in 2025. For the rest of the paper, we continue to provide results for 15 years as it brings us reasonably close to zero emissions.

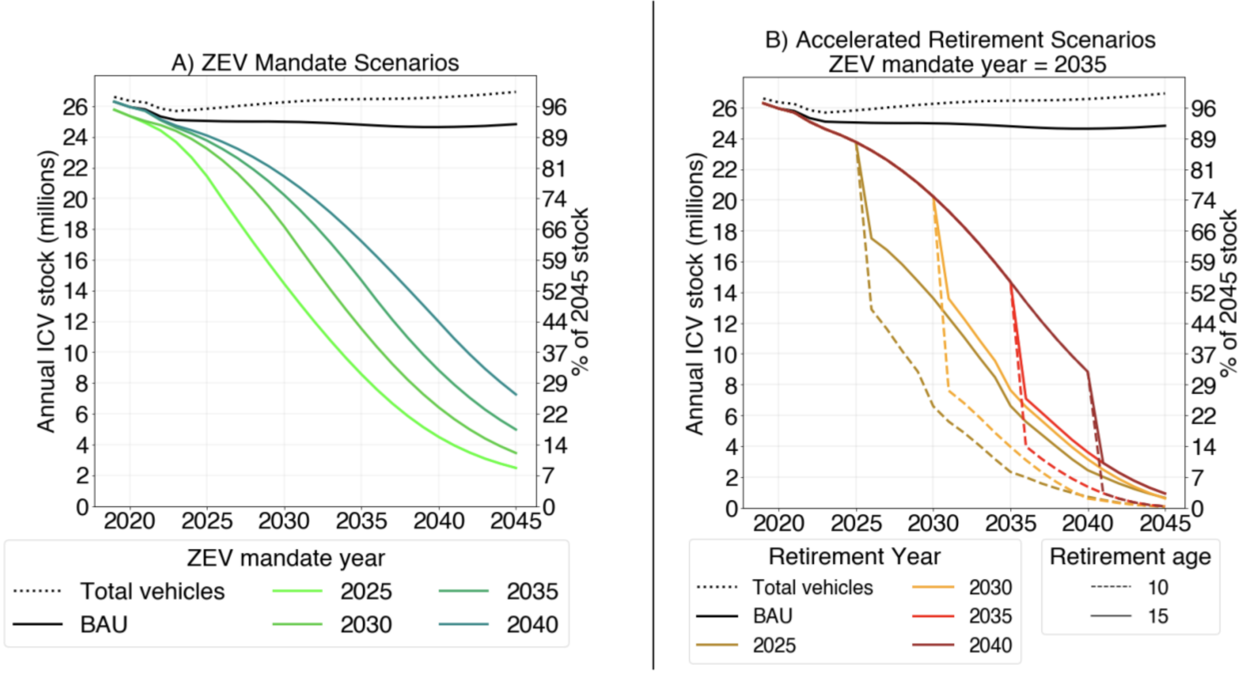
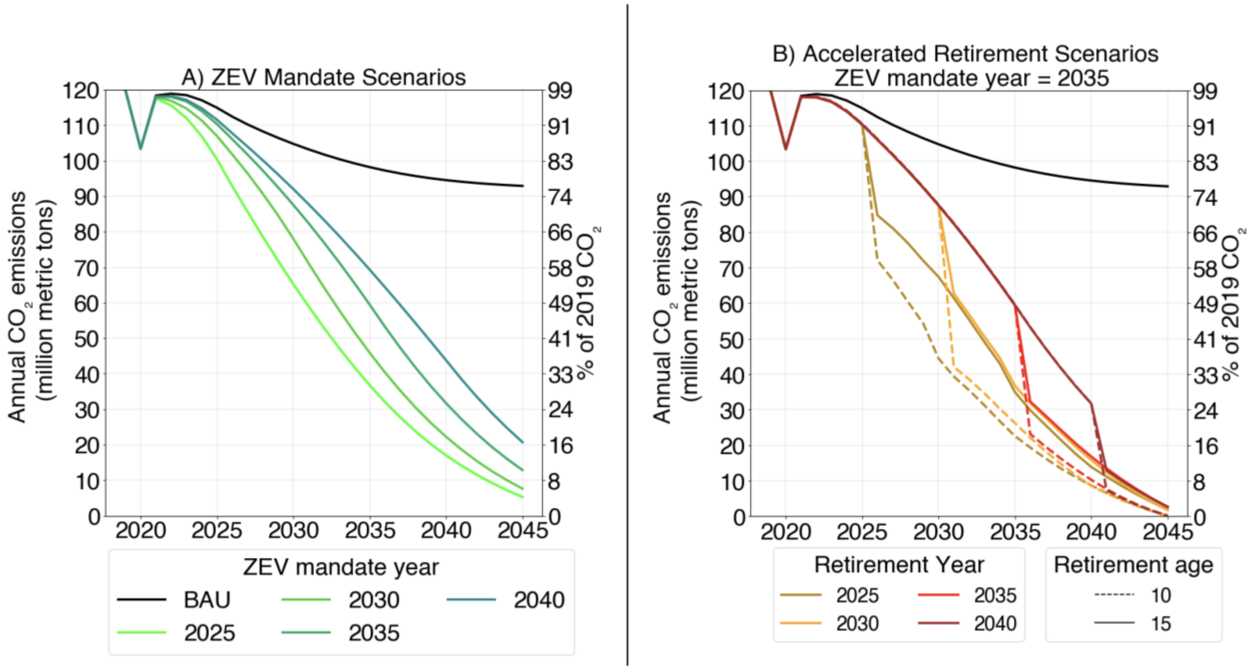


Figure 2: Stock of total vehicles and ICV in different scenarios. In panel A, we show the annual stock of ICV under BAU (solid black line) and for different ZEV mandate years. In panel B, we show the stock of ICV when an accelerated retirement policy is enacted in addition to the 2035 ZEV mandate. We consider an onset year for the early retirement policy from 2025 to 2040 and a retirement age of 10 or 15. For both panels, the dotted black line represents the total stock of vehicles (ICV + ZEV) across all scenarios.



Figures 3: Annual CO_2 emissions in different scenarios. In panel A, we show the annual CO_2 emissions of the LDV fleet (tailpipe emissions + emissions from the grid) under BAU (solid black line) and for different ZEV mandate years. In panel B, we show the CO_2 emissions of the LDV fleet (tailpipe emissions + emissions from the grid) when an accelerated retirement policy is enacted in addition to the 2035 ZEV mandate. We consider an onset year for the accelerated retirement policy ranging from 2025 to 2040 and a retirement age of 10 or 15.

Accelerated retirement significantly reduces cumulative CO_2 emissions compared to business-as-usual and ZEV mandate-only scenarios. In the BAU trajectory, LDVs in California will emit roughly 2.8 $GtCO_2$ until 2045. Under the 2035 ZEV mandate, the cumulative emissions will be roughly 1.85 $GtCO_2$, a 30% reduction compared to BAU, but the fleet will not reach zero emissions in 2045. Accelerated retirement of vehicles can ensure zero emissions by 2045 and significantly reduce cumulative CO_2 emissions between 2019 and 2045. Figure 4 shows the cumulative CO_2 emissions between 2019 and 2045 disaggregated by ICV and EV emissions by ZEV mandate year, retirement year, and retirement age. The solid bars in shades of green denote cumulative emissions for varying ZEV mandate years between 2025 and 2040, absent any accelerated retirement policy. We also show two possible ZEV mandate years – 2035 and 2045 – along with accelerated retirement policies with varying onset years and retirement ages. The colored borders of the bars denote the retirement year, and the two hatch patterns denote the retirement age - stripes for the retirement age of 15 years and circles for 10 years. We find that if the state achieves its ZEV mandate by 2035 and starts retiring vehicles older than 15 starting in 2025, cumulative emissions can be reduced by 46% compared to business-as-usual. This is 16% more emission reduction than the 2035 ZEV mandate-only scenario.

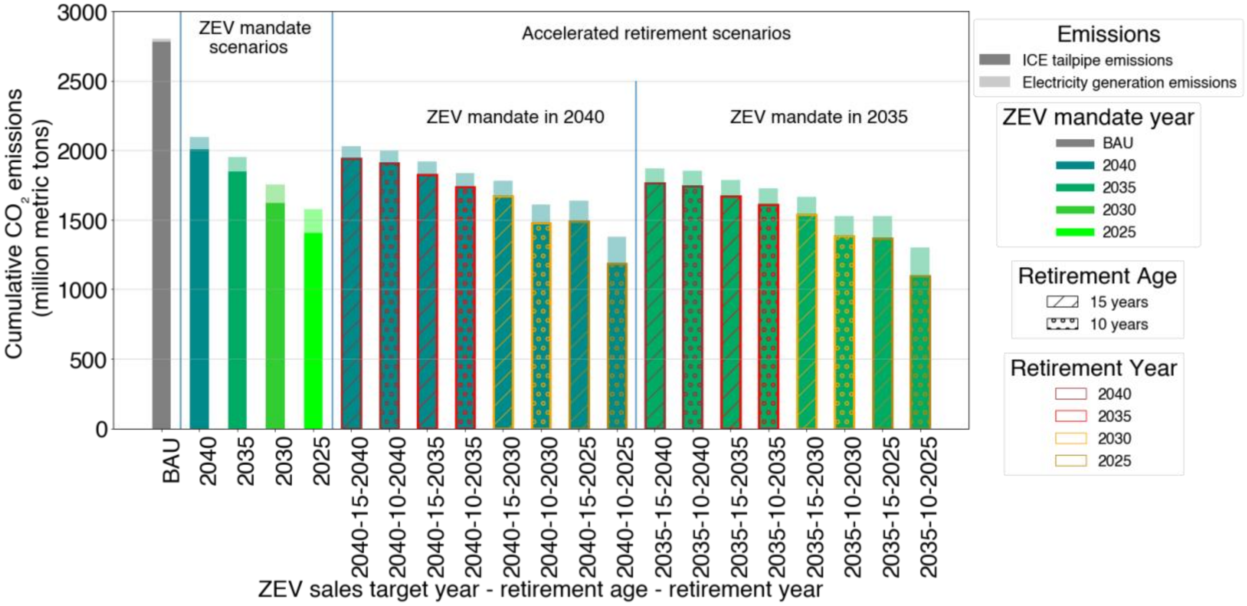


Figure 4: Cumulative CO_2 emissions from the LDV fleet in selected scenarios. The solid bars in shades of green show cumulative CO_2 emissions for varying ZEV mandate years between 2025 and 2040, absent accelerated retirement policy. The border color and hatch fill patterns for accelerated retirement policies vary with onset years and ages for the 2035 and 2040 ZEV mandate years. The retirement year is denoted by the colored borders, and the two hatch patterns show the retirement age – stripes for the retirement age of 15 years and circles for 10 years. The x-axis labels are in the form of [ZEV sales target year]-[retirement age]-[retirement year].

Accelerated retirements will also significantly reduce air pollution from light-duty transportation and associated cumulative premature mortality. In the previous sections, we showed how accelerated retirements can help California achieve its zero emissions goals by 2045 and reduce cumulative carbon emissions. However, accelerated retirements can also be a powerful tool in reducing health damages from the LDV fleet. Figures 5 A and B show annual NOx emissions from the tailpipe of ICV similar to the CO_2 curves of Figure 3. In the BAU, NOx emissions are projected to decline by almost 70% to 16 thousand metric tons by 2045. This is due to stricter air pollution emissions standards and the natural retirement of more polluting older vehicles. Under the 2035 ZEV mandate, the annual NOx emissions will reduce by almost 96% to roughly 3,000 metric tons in 2045. With accelerated retirements, we can achieve this decline much earlier and faster. For instance, an accelerated retirement policy for vehicles older than 15 years with onset in 2025 can reduce annual emissions from 48 to 18 thousand tons in a year. This rapid and early reduction of NOx emissions will significantly reduce the overall cumulative health consequences of the LDV fleet. In the BAU trajectory, LDV in California would cause ~7,000 cumulative premature deaths between 2019 and 2045. The 2035 ZEV mandate reduces this by 19%. The additional policy of retiring ICVs older than 10 or 15 years of age and replacing them with ZEVs starting in 2025 could reduce cumulative premature mortality between 2019 and 2045 by 40 to 45% compared to the BAU scenario.

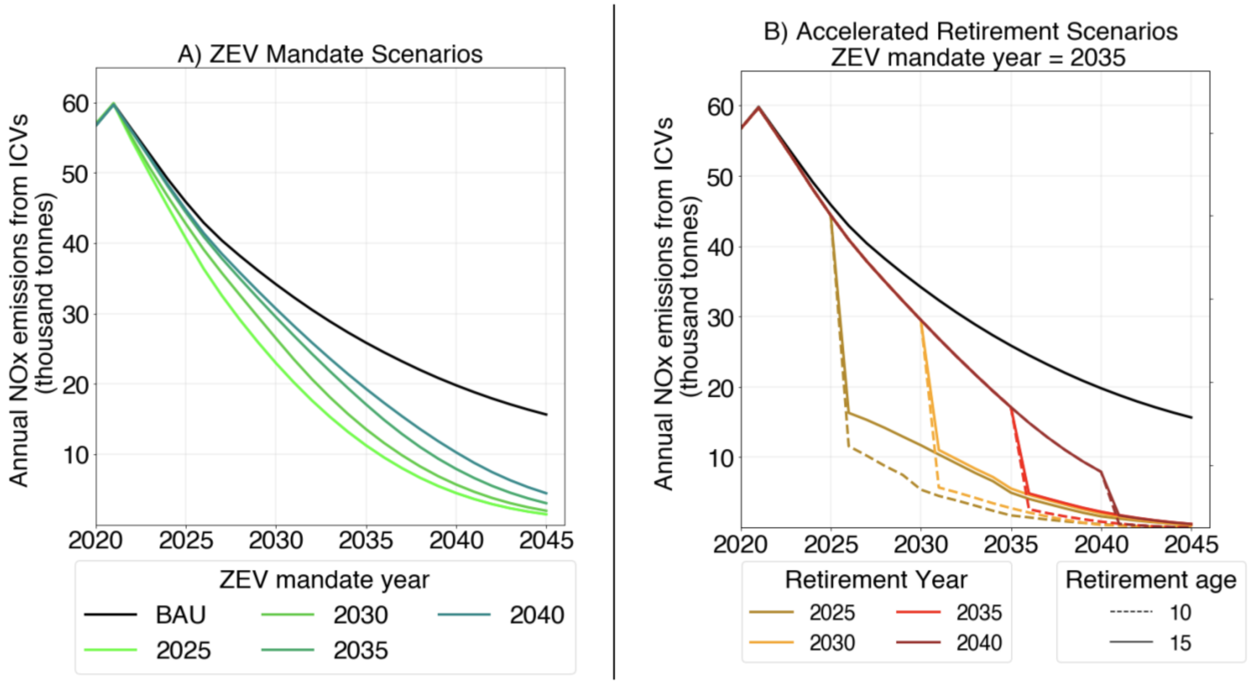


Figure 5: Annual NOx emissions from ICV in different scenarios. In panel A, we show the annual NOx emissions from ICVs (tailpipe emissions) under BAU (solid black line) and for different ZEV mandate onset years. In panel B, we show the NOx emissions from ICVs (tailpipe emissions) when an accelerated retirement policy is enacted in addition to the 2035 ZEV mandate. We consider an onset year for the accelerated retirement policy from 2025 to 2040 and a retirement age of 10 or 15.

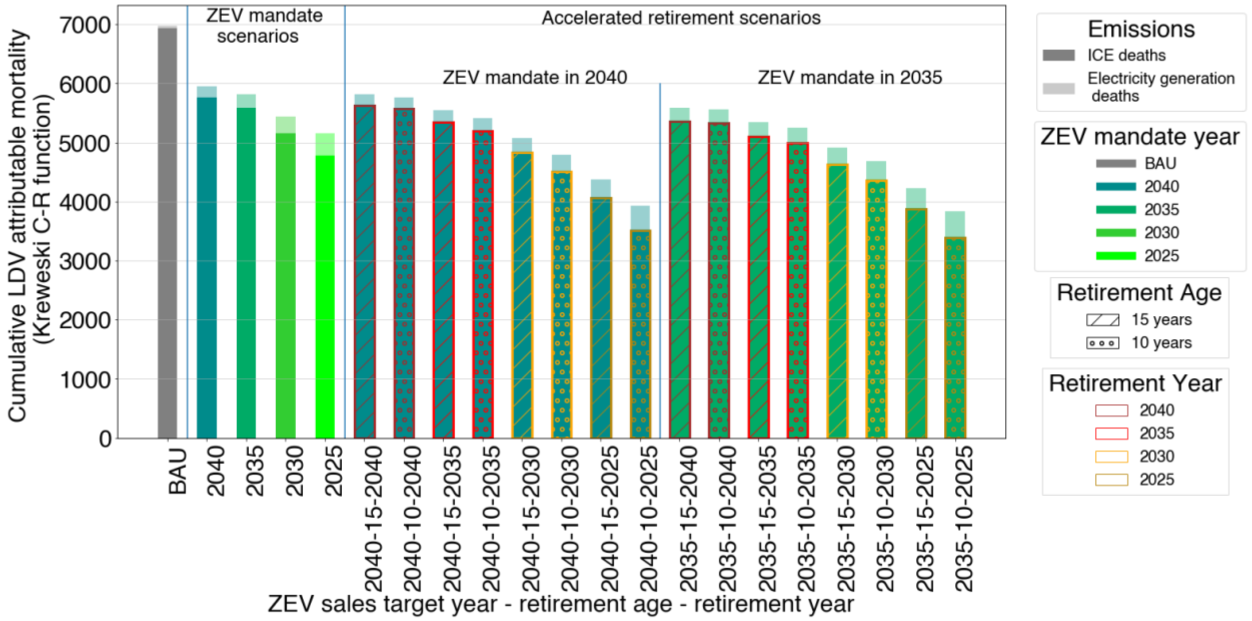


Figure 6: Cumulative premature deaths caused by exposure to $PM_{2.5}$ resulting from LDV emissions in selected scenarios between 2019 through 2045. Population and VMT distribution are

assumed to be the same for all years. The solid bars in shades of green show cumulative mortality for varying ZEV mandate years between 2025 and 2040, absent any accelerated retirement policy. The bar shade, border color, and hatch fill patterns for accelerated retirement policies vary with onset years and age for the 2035 and 2040 ZEV mandate years. The retirement year is denoted by the colored borders of bars, and the two hatch patterns show the retirement age – stripes for the retirement age of 15 years and circles for 10 years. The x-axis labels are in the form of [ZEV sales target year]-[retirement age]-[retirement year].

Costs and benefits of accelerated retirements. Accelerated retirements can help ensure California reaches zero emissions by 2045 and provide substantial air quality and carbon emissions benefits. However, retiring vehicles before their lifetime may require financial incentives for the owners, who could sell them to the lucrative second-hand market instead. Here, we model a simple illustrative case where owners are compensated $6,000 for retiring their old vehicle. According to Kelly Blue Book, a popular vehicle evaluation company, a used model year 2004 Ford F150 is priced between $3900 and $5000, and a used model year 2004 Toyota Camry is priced between roughly $4500 and $5400 in California [39]. These are the two most popular LDVs sold in the U.S. in 2023 [40]. Given these second-hand prices for two high-demand vehicle models, $6,000 would be a lucrative financial incentive to retire a 15-year-old. However, it may be insufficient to incentivize the retirement of a 10-year-old vehicle.

We compare the costs of accelerated retirements to monetized benefits of avoiding climate and health damages using the Social Cost of Carbon (for avoided CO_2) and the Value of Statistical Life (for avoided premature mortality). All costs and benefits in Figure 7 are in terms of net present value, using a discount rate of 7%. Considering both the climate change damages from greenhouse gases and health damages from air pollution is important since these are two large negative externalities from vehicle emissions. We estimate $PM_{2.5}$-related premature mortality with a reduced complexity air quality model, InMAP, and a log-linear dose-response function (see data and methods for more details) for each of our scenarios[2].

We find that the 2019 LDV fleet in California contributes to roughly ~478 $PM_{2.5}$-related premature deaths. Assuming a Value of Statistic Life of $9.97 million, this amounts to $4.7 billion of health damages per year [37]. As shown previously, LDV CO_2 in 2019 was about 120 million metric tons. At a Social Cost of Carbon of 190 $/metric tons CO_2, this amounts to $23 billion in climate damage per year. Thus, currently, the combined damages from climate change and health associated with driving these vehicles in California is about $28 billion.

In Figure 7, we provide a simple cost-benefit analysis of our accelerated retirement strategies for light-duty vehicles using an illustrative retirement cost of $6000 per vehicle. So, hypothetically, if this policy were implemented, a consumer could receive $6,000 for retiring their old vehicle and $7,500 for purchasing a new ZEV under the Inflation Reduction Act to replace it [44]. The two colors denote ZEV mandate years 2035 (red) and 2040 (blue), and the hatch patterns and marker shapes denote retirement year and age. The x-axis shows the avoided climate and health damages with accelerated retirement policies. The avoided damages are estimated by subtracting the cumulative climate and health damages under accelerated retirement scenarios from the cumulative damages under the ZEV mandate scenario of 2035 or 2040. Hence, the benefits shown below are only due to accelerated retirements, provided the ZEV mandates are met by 2035 or 2040. We find that retiring LDV older than 15 or 10 starting in 2025 is cost-effective for both mandate years. A 2025 accelerated retirement policy provides almost $45-70 billion in

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[2] We ignore $PM_{2.5}$ emissions from tire and brake wear, which are uncertain but likely to be small when compared to the emissions from vehicle operations [41], [42]. We also don't include health damages from ground-level ozone, a strong lung irritant often formed due to reactions between NOx and VOC from vehicles [43].

climate and health benefits. An earlier retirement policy provides higher avoided health damages. We also find pushing the retirement to later years is not cost-effective, given a remuneration of $6,000 and current values of the social cost of carbon and the value of statistical life.

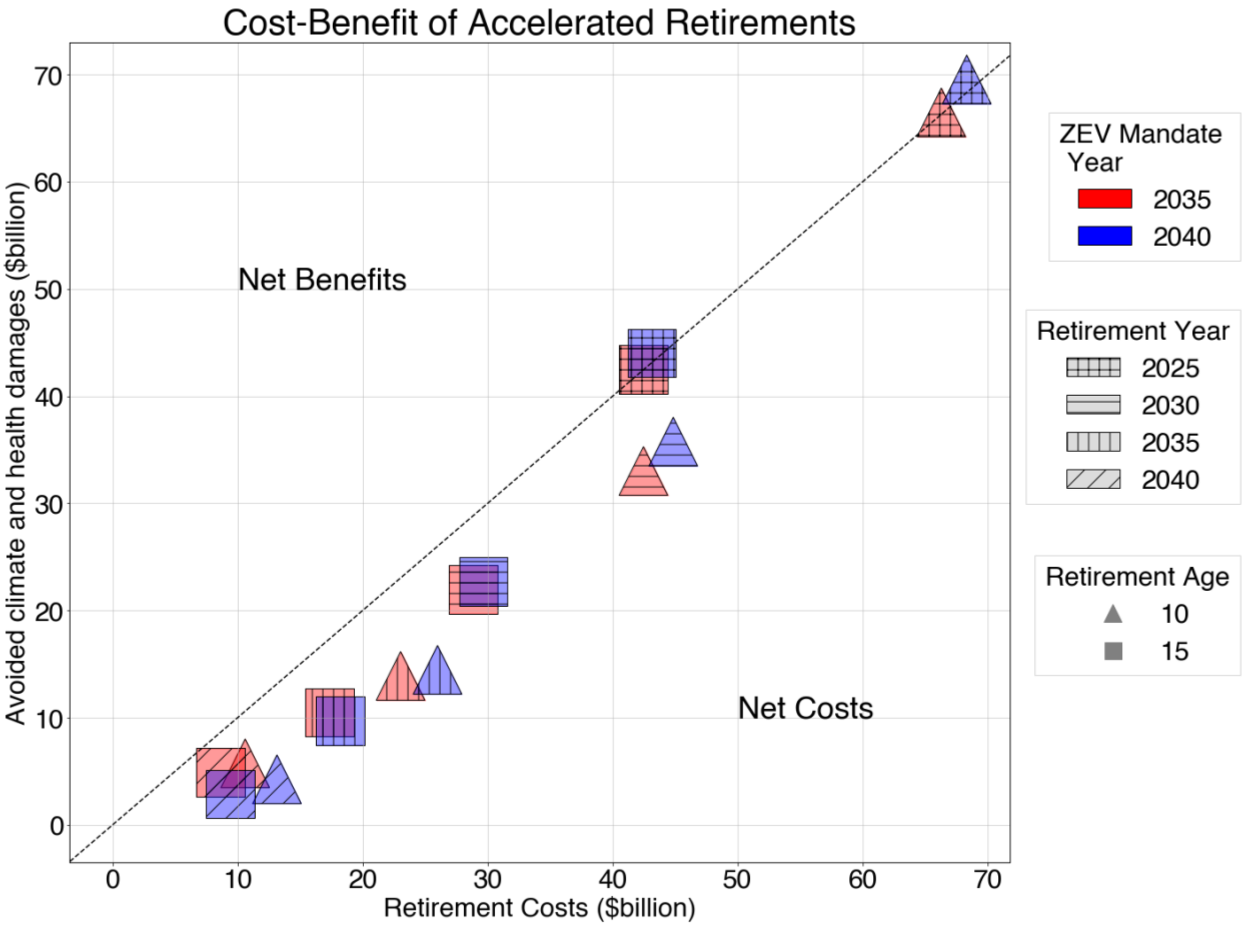

Figure 7: Present value of avoided health and climate damages vs. present value of the cost of a policy that provides $6,000 per vehicle for early retirement. The two colors denote ZEV mandate years of 2035 (red) and 2040 (blue), while the hatch patterns and marker shape denote the retirement year and age. The topmost points with crisscrossed hatch patterns denote accelerated retirements starting in 2025.

Conclusion

ZEV mandates for new vehicle sales are an important policy tool for decarbonizing LDV transportation. They will significantly reduce greenhouse gas emissions, air pollution, and $PM_{2.5}$-related premature mortality. Indeed, we find that the current policy, which consists of a mandate that all new vehicles sold in California from 2035 onwards be ZEV, can reduce annual emissions of CO_2 and NOx by 90 and 96 percent in 2045 and reduce cumulative CO_2 emissions by 0.85 $GtCO_2$ compared to business-as-usual. However, this mandate alone will not reach zero emissions from LDVs by 2045. Roughly 20% of the 2045 LDV fleet will continue to be powered by gasoline and will emit at least 13 million metric tons of CO_2 in 2045. To achieve zero emissions, the state will need to implement additional policy interventions requiring accelerated retirement of conventional vehicles.

Accelerated retirement of ICVs and their replacement with ZEVs will achieve zero emissions by 2045. These policies, especially when introduced earlier, can also lead to substantial co-benefits such as reduced air pollution and avoided premature mortality. Vehicles manufactured before 2004 contribute roughly 77% of LDV NOx in California. Compared to BAU, an accelerated retirement policy for vehicles older than 15 years starting in 2025 can reduce cumulative premature mortality by 43% (2,755 fewer deaths) as opposed to a 17% reduction under the 2035 ZEV mandate policy (1,166 fewer deaths). Well-designed accelerated retirement policies can substantially reduce both carbon emissions and air pollution.

If an incentive of $6,000 is enough to induce owners to retire their vehicles, then such a mechanism, applied to LDVs 15 years or older starting in 2025, would lead to the cumulative present value of the health and climate benefits that is larger than the cost of the incentive, and thus warranting policy intervention. While this compensation value is only for illustrative purposes, it is higher than the second-hand prices of 2004 models of currently most widely sold vehicles. Alternative policy designs can also be explored, such as higher registration costs for older vehicles [45] or increasing the ZEV tax credit to more than the current $7,500 under the Inflation Reduction Act [44] but with an old vehicle trade-in.

This work only focused on the impacts of ZEV mandates and accelerated retirements of California's LDV fleet. Other studies, including CARB’s Scoping Plan, present decarbonization pathways for zero-emissions liquid fuels such as biofuels, renewable diesel, and biomethane [2], [27]. These fuels continue to produce tailpipe air emissions and health damages and are excluded from our analysis. While EVs charged on the current electricity grid of California and WECC already have lower air emissions than ICVs [29], [46], the electricity sector must continue decarbonizing to reach net-zero emissions by 2045.

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