ENVIRONMENTAL RESEARCH
ENERGY

PERSPECTIVE • OPEN ACCESS

Vehicle scrappage policies for transportation decarbonization

IOP Publishing Environ. Res.: Energy 1 (2024) 033002 https://doi.org/10.1088/2753-3751/ad63aa

ENVIRONMENTAL RESEARCH
ENERGY

OPEN ACCESS

RECEIVED
19 March 2024

REVISED
11 July 2024

ACCEPTED FOR PUBLICATION
16 July 2024

PUBLISHED
25 July 2024

PERSPECTIVE

Vehicle scrappage policies for transportation decarbonization

Maxwell Woody[1,2,3,*], Samuel Stolper[4], Parth Vaishnav[1] and Gregory A Keoleian[1]

[1] Center for Sustainable Systems, School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, United States of America
[2] Department of Mechanical Engineering, College of Engineering, University of Michigan, Ann Arbor, MI, United States of America
[3] Science, Technology, and Public Policy Program, Ford School of Public Policy, University of Michigan, Ann Arbor, MI, United States of America
[4] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: maxwoody@umich.edu

Keywords: electric vehicles, scrappage programs, transportation, decarbonization, GHG emissions, policy

Abstract

Vehicle electrification is one of the primary strategies being pursued for the decarbonization of the transportation sector. But to meet emissions reduction goals for that sector, the current vehicle replacement rate is insufficient. Vehicle scrappage policies can accelerate fleet turnover by providing an incentive to retire a vehicle before its natural end of life and simultaneously replace it with a more efficient or less polluting alternative. Previous scrappage programs, like the United States' Cash for Clunkers, have had limited success as decarbonization policies; however, most of these programs ended before the widespread availability of electric vehicles and did not have decarbonization as a primary policy goal. Here we explain why scrappage policies may be necessary to meet climate goals, review historic vehicle scrappage policies from a variety of countries, highlight the successes and failures of those policies, and establish policy design considerations that could help ensure that future scrappage programs are more successful than previous efforts.

1. Introduction

The U.S. aims to reduce economy wide greenhouse gas (GHG) emissions by 50% (from 2005 levels) by 2030, and to net zero by 2050, in line with international climate agreements. Decarbonizing transportation—the highest-emitting sector in the U.S. economy—is essential to meeting these climate goals [1]. While the U.S. aims to electrify 50% of light duty vehicle sales by 2030 [2], even if these electric vehicle (EV) sales targets are met, the U.S. transportation sector would fall short of the economy wide 2030 emissions target [3]. One major obstacle is the slow pace of vehicle fleet turnover [4, 5]. Because the average vehicle lifespan is approaching 20 years [6], reaching 50% EV sales in 2030 may result in only 10% of the on-road fleet being electric in that year [3]. Deeper and faster transportation decarbonization requires efforts to accelerate fleet turnover.

Vehicle scrappage programs have the potential to accelerate fleet turnover by providing monetary incentives for simultaneously retiring an old vehicle and purchasing a new one [7]. The emissions impact of a scrappage policy fundamentally depends on how it affects both the timing of purchases and which vehicles are purchased. Previous scrappage programs (e.g. 'Cash for Clunkers' (CfC)) have been rationalized as economic stimulus policies, bringing consumer spending (vehicle purchases) forward in time. However, many have also been designed to encourage more energy efficient vehicles through the choice of which old and new vehicles qualify.

The efficacy of such policies for decarbonization is inconsistent, with significant geographic variability and with recent research [8, 9] on Great Recession-era programs demonstrating more promising results than earlier studies [10–12]. Here we review the impacts of various vehicle scrappage programs, focusing on key design elements. We then highlight research opportunities and policy considerations that could inform future successful scrappage programs and hasten decarbonization.

2. Evidence from scrappage programs

Scrappage policies have proven quite politically palatable: at least 19 countries spanning three continents have enacted national programs since 2000, with U.S. states (California, Vermont, and Colorado) enacting new programs in 2014, 2021, and 2023, respectively. Here we compare several of the largest national policies, in the U.S., Germany, Japan, and France, as well as California's state scrappage program (table 1). Key elements of the programs include total budget, duration, eligibility, subsidy per vehicle, and the required attributes of both the scrapped vehicle and its replacement. Key outcomes include the total number of vehicles replaced, the number of vehicle replacements induced by the policy, and the total and per dollar reductions in GHG emissions. However, as many past programs were designed as stimulus policies, and several contemporary programs are designed to reduce inequities, $/ton GHG reduced is not a holistic metric by which to judge program success.

2.1. United States (Cash for Clunkers)

In 2009, the U.S. launched the Car Allowance Rebate System CfC to reduce GHG emissions and air pollution, reduce economic inequality, and stimulate the economy. The program lasted 2 months, cost $3 billion, and provided consumers with $3500-$4500 per vehicle replaced. Though 680 000 vehicles were replaced, CfC had limited success as a decarbonization policy. Estimates of induced vehicle replacements range from 370 000 [10, 11] to 500 000 [9] (i.e. the remainder would have been replaced during the two months of the program even in its absence). Additionally, comparisons of historic average vehicle sales with sales in the months following the program's end showed a decline in sales equal to the quantity of induced purchases [10, 11]. This means induced vehicle purchases were 'pulled forward' by less than a year (i.e. all the vehicles replaced under the program would have been replaced within a year even without the program). CfC imposed relatively modest rules on vehicle eligibility, with new vehicles needing 2 MPG (trucks) or 4 MPG (cars) improvement over the scrapped vehicle. On average, the difference in fuel economy between scrapped and replaced vehicles was 8.5 MPG [13]. Due to this improved fuel economy, GHG emissions may have been reduced by 9–28 million tons CO_2, with an implied cost of $92-$–288/ton [11]. However, when vehicle production emissions are included, the reduction in emissions may have been as low as 4.4 million tons CO_2 (roughly $650/ton), demonstrating the importance of accounting for a vehicle's full life cycle [13].

2.2. Germany (Umweltprämie)

Germany also established a vehicle scrappage program in 2009. Compared to CfC, the German program had a larger budget and lasted longer, replacing 2 million vehicles (with up to 50% estimated to be purchases induced by the program). The German passenger car fleet was approximately 30% of the U.S. fleet in 2009, so proportionally the differences were even larger. Ultimately 4.8% of the German vehicle fleet was replaced [8]. As in the U.S., vehicle restrictions were minimal. Replacement vehicles had to meet the Euro 4 emissions standard, which was met by all new vehicles at the time.

Unlike in the U.S., there is little evidence that vehicle purchases were pulled forward from the immediately following months or years, as German car purchases reverted to original levels following the end of the program [8]. This suggests the German program was more successful at accelerating the turnover of the vehicle fleet. But it is not known what characteristics of the German policy, if any, explain its more auspicious outcomes. Helm *et al* estimate 22.7 billion EUR in benefits from the program (exceeding the program's 5 billion EUR cost) from the impact of improved air quality on human health resulting from a 7% decrease in NO_2 emissions [8].

2.3. Japan (Eco-Car)

Japan's Eco-car scrappage program spent approximately 2.3 billion between April 2009 and September 2010 [14]. Consumers received ∼$2500 to spend on a standard or small car or ∼$1250 for a mini-vehicle when replacing a vehicle at least 13 years old. The replacement vehicle had to meet Japan's 2010 fuel efficiency standards, a threshold met by 78.5% of models for sale at the time. Japan's program also included incentives ranging from ∼$4000 to ∼$18 000 for retiring and replacing various heavy-duty trucks and buses [15]. Approximately 730 000 vehicles were scrapped as part of the program, with an estimated 9.4 MPG difference between scrapped vehicles and their replacements [14]. Following the end of the program, sales declined sharply and fell below pre-implementation levels, showing that many vehicle purchases were pulled forward from the near future [16]. Because of the modest qualification standards for replacement vehicles, Kagawa *et al* estimate the life cycle GHG reduction from the program as 1 million tons of CO_2e ($2300/ton) but show that if the replacement vehicles had been limited to hybrid EV, the savings could have been approximately 8.4 million tons ($275/ton) [14]. They also suggest that the target age of 13 years was not optimal, and that a

Table 1. Key policy design choices and outcomes from select vehicle scrappage programs.

	United States (Cash for Clunkers)	Germany (*Umweltprämie*)	France (Prime à la Casse)	Japan (Eco-Car)	California (Clean Cars 4 All)
Program size	$2.85 billion USD	$6.8 billion USD	$850 million USD	$2.3 billion USD	$114 million USD
Program duration	2 months (2009)	9 months (2009)	4 years (2008–2011)	16 months (2009–2010)	9 years (2015-present)
Subsidy level per vehicle	3500–4500 USD	3400 USD	430–1430 USD	1031–2577 USD	7500–9500 USD
Scrapped vehicle eligibility	- At least 4 MPG worse than replacement (cars) - At least 2 MPG worse than replacement (trucks) - Less than 25 years old	- 9 years old or older	- 10 years old or older - 15 years old or older	- 13 years old or older	- Model year 2005 or older
Replacement vehicle eligibility	- At least 22 MPG (cars) - At least 18 MPG (trucks) - New vehicle - Under $45 000	- Complies with Euro 4 emissions standard - New vehicle	- Maximum of 160, 155, or 150 g CO2 km^{-1} - New vehicle	- Complies with Japan's 2010 fuel efficiency standard - New vehicle	- HEV, PHEV, BEV, FCEV, or mobility option - New or used, but 8 years old or newer
Participant eligibility	No restrictions	No restrictions	No restrictions	No restrictions	- Income requirements (300% of federal poverty level) - Residence requirements (disadvant-aged community)
Total vehicles scrapped	680 000	2000 000	550 000	730 000	17 000
Estimated induced vehicle scrappage	370 000–500 000 [9, 10]	600 000–1000 000 [8, 16]	220 000 [18]	N/A	N/A
Estimated life cycle GHG emissions reduction cost	$650/ton [13]	N/A	N/A	$2,300/ton [14]	$1,100/ton [22]

target age of 9 years (when combined with limiting replacements to hybrids) would have increased the savings to 8.8 million tons ($261/ton) [14].

2.4. France (Prime à la Casse)

France's vehicle scrappage program was renewed for several years with incentives that began at 1000 EUR (in 2009) before declining over time to 750 and 500 EUR (2010) and 300 EUR (2011). This led to more vehicles (550,000) being replaced per amount spent on the program (~850 million USD), than in other countries explored here [17]. The slow phase-out of the program also differed from the abrupt ending of programs in the U.S., Germany, and Japan. The emissions requirement for replacement vehicles became stricter over time, declining from 160 to 155 to 150 g CO_2e km^{-1} [18]. Grigolon *et al* show that these more targeted standards for replacement vehicles led to greater improvements in fuel efficiency. They estimate that in France, the replacement vehicles had 3.8% lower fuel consumption than the vehicles consumers would have purchased without the program. In contrast, they estimate the reduction at 1.5% in Germany, where all new vehicles met the emissions standard to be eligible as replacements [18].

2.5. California (Clean Cars 4 All)

California's Clean Cars 4 All (CC4A) is a current vehicle scrappage program, originally limited to certain air quality districts, but now being expanded statewide. CC4A differs from historic national programs by focusing on low-income communities, providing much larger subsidies, and including stricter eligibility rules for both scrapped vehicles and their replacements. The program reports a cumulative savings of 140 000 tons CO_2e, as well as 137 tons of Nitrogen Oxides (NO_x) and 5 tons of particulate matter [19]. Of vehicles scrapped under CC4A thus far, 14% were replaced with EVs, 50% with plug-in hybrids, 32% with traditional hybrids, and 3% with internal combustion engine vehicles [20]. Of the participating households, 87% were under 225% of the federal poverty level, and 97% were under 300% of the federal poverty level [21]. For this policy, it is estimated that $1100 has been spent per ton of CO_2e removed [22]. This far surpasses the $200/ton CO_2e cost of California's traditional EV subsidy, the Clean Vehicle Rebate Program (CVRP) [22]. New scrappage policies in Colorado and Vermont have similar rules, limiting replacement vehicles to electric options, and restricting eligibility to include only low-income residents.

3. Key considerations for scrappage programs

Though the existing research on scrappage programs shows mixed performance, it highlights the importance of policy design and opens significant research questions. The effect of a scrappage program on GHG emissions is a product of the miles of travel replaced per vehicle, the change in emissions per mile, and the number of people (vehicles) induced to participate in the program (table 2). At the same time, transportation justice depends on who participates in the program and who experiences the air quality benefits. Decisions about policy parameters—the total budget, subsidy per vehicle, acceptable attributes of scrapped and replacement vehicles—affect each of these program outcomes.

3.1. Maximizing mileage replaced per vehicle

A scrappage policy aims to induce drivers to pull forward their next vehicle purchase from the future. The larger the length of time of the pull-forward effect, the more miles of old-vehicle use are being replaced, which translates to greater emissions reductions. Evaluations of the CfC program highlight small pull-forward effects and emissions reductions [9–11, 13], with one study estimating that the average scrapped vehicle may have had only 22 000 miles of useful life left [13]. Age or mileage caps may help address this concern. A critical research question is why Germany's scrappage program—which had similar vehicle eligibility rules yet demonstrated large pull-forward effects and air quality improvements—was significantly more successful [8].

To ensure that mileage is replaced, retired vehicles must be scrapped rather than resold. In the U.S., CfC required that a vehicle's motor oil was replaced with sodium silicate, permanently disabling the vehicle and making resale (or reuse of the engine in a different vehicle) impossible. In Germany, dealers only had to deliver retired vehicles to junkyards, which resulted in up to 50 000 vehicles being illegally resold and exported to Africa and Eastern Europe [23]. If an exported vehicle is added to the vehicle fleet in the importing country, then the benefits of the scrappage program would be smaller than estimated (as the dirty miles are not in fact replaced). However, if the retired and exported vehicle induces the scrappage of an even dirtier vehicle in the importing country, then benefits of the scrappage program would be greater than estimated (as the difference between the new vehicle and the vehicle it ultimately replaces is larger). If robust monitoring schemes were established, international partnerships could increase the benefits of scrappage programs.

3.2. Maximizing change in emissions per vehicle

To maximize the emissions reduction for each scrapped vehicle, programs can target high-emitting vehicles for retirement, target low-emitting vehicles as replacements, and encourage other modes of transportation. Targeted replacement of high-emitting vehicles is not trivial, however. There are several potential proxies for high-emissions vehicles, including vehicle age, size, and use (miles traveled), that could be used to define eligibility. However, the older and higher mileage vehicles that tend to have higher emissions are also more likely to be near their end-of-life. Thus, there are tradeoffs to consider when determining scrapped vehicle eligibility rules. Due to either high annual mileage, relatively high emissions per mile, or both, vehicles to

Table 2. Key considerations for successful decarbonization through vehicle scrappage programs.

Goal	Strategy	Policy Design Choices	Considerations
Maximize mileage replaced per vehicle	Encourage purchases pulled forward from further in the future	Size/duration of program Subsidy level per vehicle	More research is needed to determine how program size, duration, and subsidy levels impact the pull-forward effect on vehicle replacement.
		Scrapped vehicle eligibility	An age limit or mileage cap on the scrapped vehicle may reduce non-additional program participation, e.g. by drivers of old vehicles about to be scrapped anyways
	Ensure retired vehicles are scrapped	Scrapped vehicle eligibility	A requirement to permanently disable the engine can avoid illegal resale and export
Maximize change in emissions per vehicle	Target high-emitting vehicles for retirement	Scrapped vehicle eligibility	Older vehicles tend to be higher emitting; thus, age limits may miss some of the best vehicles to replace Limiting scrapped vehicle eligibility to ICEVs would raise emissions reductions per vehicle
	Target low-emitting vehicles for replacement	Replacement vehicle eligibility	Scaling the subsidy level with vehicle efficiency may be cost-effective Limiting replacement vehicle eligibility to EVs would raise emissions reductions per vehicle Prioritizing EV deployment in regions with low-carbon electric grids would raise emissions reductions per vehicle
	Provide and encourage other modes of transportation	Subsidy level	Providing subsidies for other modes—e.g. \$3,000 towards an e-bike or transit passes vs \$2,000 for a vehicle—may induce especially impactful vehicle scrappage
		Complementary policies	Scrappage programs could be combined with other policies (e.g. public transit investment) that support different modes
Achieve program participation goals	Optimize subsidy design	Subsidy level per vehicle	Higher subsidy levels may increase participation, but if the policy's total budget is binding, then smaller subsidy levels may be more efficient
		Subsidy structure	Making the subsidy available at the point of sale can significantly increase participation by providing households with liquidity
Support transportation justice	Consider distributive and procedural fairness in policy design	Subsidy level	Scaling the subsidy level to be higher at lower incomes could increase participation at lower levels of income
		Replacement vehicle eligibility	Making used EVs eligible to be a replacement vehicle could increase participation at lower income levels
		Participant eligibility	Giving priority to lower-income or higher pollution areas would support distributive justice
		Program Administration	Reducing administrative barriers and investing in community engagement would promote procedural justice and access to program benefits

prioritize for scrappage could include ride-hailing vehicles [24], fleet vehicles (e.g. buses) [25], and medium and some heavy-duty vehicles (e.g. delivery vehicles) [26].

For replacement vehicles, not all previous scrappage policies established eligibility rules. Grigolon *et al* compare European scrappage programs and find that policies targeting more fuel-efficient vehicle purchases (France, Italy, Portugal, Spain) reduced fuel consumption by 3.6% on average, while those allowing any new vehicle to be purchased (e.g. Germany, Netherlands, UK) reduced fuel consumption by 0.7% on average [18]. Naumov *et al* model a hypothetical vehicle scrappage program in the U.S. showing an emissions reduction cost of \$613 to \$1233 per ton CO_2 with no EV requirement (with \$4000 and \$8000 scrappage incentives, respectively) but \$56 to \$124/ton CO_2 *with* such a requirement [27]. Notably, less than 20% of the emissions reduction comes from the short-run effect of the subsidy on EV purchases; the remainder come from follow-on effects such as accelerated charging infrastructure deployment, increased model availability, and decreased EV production costs, all of which drive further increases in EV purchases in the longer run [27].

Due to spatio-temporal variation in the carbon intensity of the electric grid, EV emissions depend not only on the vehicle itself, but also on the location and timing of charging, opening opportunities for geographically targeted programs [28]. EV emissions also depend on how the electricity generation mix changes over the lifetime of the vehicles, making efforts towards grid decarbonization and air pollutant reduction important determinants of scrappage program outcomes. Increased penetration of renewables could be paired with smart-charging capabilities to further enhance the emissions benefits of EVs [29]. In many cases, electrification also has human health co-benefits from reductions in local air pollution [30], but additional research is needed to evaluate these benefits in the context of vehicle scrappage policies and alongside a rapidly evolving electricity grid.

While replacing an old vehicle with a new vehicle—especially an EV—generally reduces emissions [28], the impact of replacement would be even greater if retired vehicles were replaced with alternative modes like public transit, walking, or biking [31]. California's CC4A program includes the option to use money from the scrapped vehicle to obtain transit passes, bikes, or electric bikes, yet only 0.5% of participants have opted for these alternatives [20]. By increasing incentives for alternative replacement modes, and by taking steps to increase their viability (e.g. through city design, increased infrastructure spending, or paired subsidy programs), the impact of a vehicle scrappage policy may be amplified.

3.3. Maximizing program participation

All else equal, greater vehicle replacement will result in greater emissions reductions. A larger subsidy attracts more would-be program participants, but if the government's program budget is limited, then the larger subsidy may end up causing *fewer* vehicle purchases (before all the money is spent). For example, observing U.S. CfC funds dwindle rapidly, Lenski *et al* theorize that a lower subsidy level spread across more participants could have achieved greater environmental benefits for the same total cost [32]. Studying participation elasticities with respect to subsidy levels may help determine the optimal scrappage subsidy level given a budget constraint. Furthermore, the subsidy should likely take the form of time-of-purchase rebate rather than a tax credit; Green *et al* show that the liquidity provided by making the CfC scrappage subsidy usable as a down payment was critical to program participation [9].

3.4. Supporting transportation justice

While much attention has been paid to estimating scrappage policy impacts on vehicle purchases and environmental outcomes, there has been little coverage of fairness-related questions about such policies. Additional research is needed on how scrappage subsidy dollars and air quality improvements have been distributed across households, how much of the subsidy has been passed through to consumers rather than captured by vehicle sellers, and how scrappage programs may impact used vehicle markets, as prices in these markets are an important determinant of vehicle affordability.

Historically, EV subsidies have benefitted those who could already afford to purchase a new vehicle. For example, the CVRP in California issued more rebates per household to higher income communities with more white residents [33]. Allowing used EVs as eligible replacement vehicles may improve distributional equity of subsidy take-up [31]. Scrappage policies explicitly focused on justice (like CC4A) have been more effective at distributing resources to disadvantaged communities and have the potential to improve transportation reliability and accessibility, but have still struggled with burdensome documentation requirements, strict timelines, and poor community engagement [34]. Focusing on locations with high air pollution may make the distribution of co-benefits more equitable [35]. Minimizing administrative barriers and improving communication can improve distributive and procedural fairness.

4. Outlook on scrappage programs

Historic vehicle scrappage programs from the Great Recession era were primarily designed as stimulus policies, not environmental policies, and took place when EV sales were nearly nonexistent. It was not until 2016 that EVs (BEVs and PHEVs) became 1% of new vehicle sales (both in the U.S. and globally). By 2023, EVs reached 9.5% of sales in the U.S. and 18% of sales globally [36]. At the same time, the U.S. reached a record high average on-road vehicle age (12.6 years) in 2024 [37]. The growth of the EV industry combined with the relatively old U.S. vehicle fleet provides an opportunity for scrappage programs to provide greater and more cost-effective emissions reductions than previous efforts, especially if replacement vehicle eligibility is limited to EVs, and high mileage, high-emitting vehicles are prioritized for scrappage. While table 2 provides important factors to consider when designing a vehicle scrappage program, implementation of these programs should be evaluated in the context of existing policies (e.g. EV incentives and fuel economy regulations) to avoid unintended consequences of policy interactions [38], and alongside additional transportation decarbonization mechanisms to build synergistic policy mixes [39].

The transition to EV is not occurring fast enough to meet national and international climate goals for the transportation sector. Vehicle scrappage policies should be considered to accelerate fleet turnover. With the rise of EVs since the Great Recession-era wave of scrappage programs, contemporary scrappage policies offer new potential for hastening decarbonization. With careful policy design to improve on previous efforts, and incorporation into a broader policy suite, vehicle scrappage programs could be a critical component of a comprehensive transportation decarbonization plan.

Data availability statement

No new data were created or analysed in this study.

ORCID iDs

Maxwell Woody https://orcid.org/0000-0002-6610-2777
Samuel Stolper https://orcid.org/0000-0001-7250-8039
Parth Vaishnav https://orcid.org/0000-0003-1582-4523
Gregory A Keoleian https://orcid.org/0000-0002-7096-1304

References

[1] Bistline J *et al* 2022 Actions for reducing US emissions at least 50% by 2030 *Science* **376** 922–4
[2] U.S. Department of Energy 2023 *The U.S. National Blueprint for Transportation Decarbonization* (available at: www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf)
[3] Woody M, Keoleian G A and Vaishnav P 2023 Decarbonization potential of electrifying 50% of U.S. light-duty vehicle sales by 2030 *Nat. Commun.* **14** 7077
[4] Alarfaj A F, Griffin W M and Samaras C 2020 Decarbonizing US passenger vehicle transport under electrification and automation uncertainty has a travel budget *Environ. Res. Lett.* **15** 0940c2
[5] Milovanoff A, Posen I D and MacLean H L 2020 Electrification of light-duty vehicle fleet alone will not meet mitigation targets *Nat. Clim. Change* **10** 1102–7
[6] Leard B and Greene D 2023 Coordinating the electric vehicle transition and electricity grid decarbonization in the U.S. is not essential to achieving substantial long-term carbon dioxide emissions reductions *Environ. Res. Lett.* **18** 074035
[7] Keith D R, Houston S and Naumov S 2019 Vehicle fleet turnover and the future of fuel economy *Environ. Res. Lett.* **14** 021001
[8] Helm I, Koch N and Rohlf A 2023 The effects of cash for clunkers on local air quality *CESifo Working Paper* (available at: www.cesifo.org/DocDL/cesifo1_wp10530.pdf)
[9] Green D, Melzer B T, Parker J A and Rojas A 2020 Accelerator or brake? Cash for clunkers, household liquidity, and aggregate demand *Am. Econ. J. Econ. Policy* **12** 178–211
[10] Mian A and Sufi A 2012 The effects of fiscal stimulus: evidence from the 2009 cash for clunkers program *Q. J. Econ.* **127** 1107–42
[11] Li S, Linn J and Spiller E 2013 Evaluating 'Cash-for-Clunkers': program effects on auto sales and the environment *J. Environ. Econ. Manage.* **65** 175–93
[12] Zolnik E J 2012 Estimates of statewide and nationwide carbon dioxide emission reductions and their costs from 'Cash for Clunkers' *J. Transp. Geogr.* **24** 271–81
[13] Lenski S M, Keoleian G A and Bolon K M 2010 The impact of 'Cash for Clunkers' on greenhouse gas emissions: a life cycle perspective *Environ. Res. Lett.* **5** 044003
[14] Kagawa S, Hubacek K, Nansai K, Kataoka M, Managi S, Suh S and Kudoh Y 2013 Better cars or older cars?: Assessing CO_2 emission reduction potential of passenger vehicle replacement programs *Glob. Environ. Change* **23** 1807–18
[15] Japanese Automobile Manufacturers Association *Japanese Government Incentives for the Purchase of Environmentally Friendly Vehicles* (available at: www.jama.org/japanese-government-incentives-purchase-environmentally-friendly-vehicles/)
[16] Lüth H 2021 Reassessing car scrappage schemes in selected OECD countries: a synthetic control method application *Discussion Paper No. 190, Helmut-Schmidt-University Hanburg* (available at: www.hsu-hh.de/fgvwl/wp-content/uploads/sites/572/2021/05/WP190.pdf)
[17] OECD/ITF 2011 *Car Fleet Renewal Schemes: Environmental and Safety Impacts* (available at: www.globalfueleconomy.org)
[18] Grigolon L, Leheyda N and Verboven F 2016 Scrapping subsidies during the financial crisis—evidence from Europe *Int. J. Ind. Organ.* **44** 41–59
[19] California Air Resources Board 2024 *Outcomes and Results for Clean Cars 4 All* (available at: https://ww2.arb.ca.gov/our-work/programs/clean-cars-4-all/outcomes-and-results-clean-cars-4-all)
[20] California Air Resources Board—Mobile Source Control Division 2023 *EFMP Retire and Replace Program Statistics* (available at: https://ww2.arb.ca.gov/sites/default/files/2023-06/EFMP%20Website%20Statistics%20Tables_through%20Q1_2023%20v1.pdf)
[21] California Climate Investments 2022 *2022 Mid-Year Data Update* (available at: https://ww2.arb.ca.gov/sites/default/files/auction-proceeds/cci_2022_mydu_cumulativeoutcomes.pdf)
[22] California Climate Investments 2023 *2023 Annual Report Cap-and-Trade Auction Proceeds* (available at: https://ww2.arb.ca.gov/sites/default/files/auction-proceeds/cci_annual_report_2023.pdf)
[23] Dougherty C 2009 Driving out of Germany, to pollute another day (The New York Times) (available at: www.nytimes.com/2009/08/08/world/europe/08germany.html?hpw)
[24] Jenn A 2020 Emissions benefits of electric vehicles in Uber and Lyft ride-hailing services *Nat. Energy* **5** 520–5

[25] Martinez S S and Samaras C 2024 Electrification of transit buses in the United States reduces greenhouse gas emissions *Environ. Sci. Technol.* **58** 4137–44

[26] Woody M, Vaishnav P, Craig M T and Keoleian G A 2022 Life cycle greenhouse gas emissions of the USPS next-generation delivery vehicle fleet *Environ. Sci. Technol.* **56** 13391–7

[27] Naumov S, Keith D R and Sterman J D 2022 Accelerating vehicle fleet turnover to achieve sustainable mobility goals *J. Oper Manage.* **69** 36–66

[28] Woody M, Vaishnav P, Keoleian G A, De Kleine R, Kim H C, Anderson J E and Wallington T J 2022 The role of pickup truck electrification in the decarbonization of light-duty vehicles *Environ. Res. Lett.* **17** 034031

[29] Cheng A J, Tarroja B, Shaffer B and Samuelsen S 2018 Comparing the emissions benefits of centralized vs. decentralized electric vehicle smart charging approaches: a case study of the year 2030 California electric grid *J. Power Sources* **401** 175–85

[30] Bistline J E T, Blanford G, Grant J, Knipping E, McCollum D L, Nopmongcol U, Scarth H, Shah T and Yarwood G 2022 Economy-wide evaluation of CO2 and air quality impacts of electrification in the United States *Nat. Commun.* **13**

[31] Nunes A, Woodley L and Rossetti P 2022 Re-thinking procurement incentives for electric vehicles to achieve net-zero emissions *Nat. Sustain.* **5** 527–32

[32] Lenski S M, Keoleian G A and Moore M R 2013 An assessment of two environmental and economic benefits of 'Cash for Clunkers' *Ecol. Econ.* **96** 173–80

[33] Ju Y, Cushing L J and Morello-Frosch R 2020 An equity analysis of clean vehicle rebate programs in California *Clim. Change* **162** 2087–105

[34] Jo-Marie Litong T and Syal S M 2023 Uncovering the barriers and inequities of a clean mobility program using journey mapping *102nd Transportation Research Board Annual Meeting* (*Washington, DC 2023)*

[35] Garcia E, Johnston J, McConnell R, Palinkas L and Eckel S P 2023 California's early transition to electric vehicles: observed health and air quality co-benefits *Sci. Total Environ.* **867** 161761

[36] International Energy Agency 2024 *Global EV Data Explorer* (available at: www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer) (Accessed 21 May 2024)

[37] Krishner T 2024 *AP News* (available at: https://apnews.com/article/average-vehicle-age-record-prices-high-5f8413179f077a34e7589230ebbca13d) (Accessed 24 May 2024)

[38] Jenn A, Azevedo I L and Michalek J J 2019 Alternative-fuel-vehicle policy interactions increase U.S. greenhouse gas emissions *Transp. Res.* A **124** 396–407

[39] Axsen J, Plötz P and Wolinetz M 2020 Crafting strong, integrated policy mixes for deep CO_2 mitigation in road transport *Nat. Clim. Change* **10** 809–18