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Stock Turnover and the Decarbonization of U.S. Passenger Vehicles

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Stock Turnover and the Decarbonization of U.S. Passenger Vehicles

Abstract. Relevant features that define how quickly the US can decarbonize passenger vehicles include the rate of stock turnover, defined as how quickly new vehicles replace scrapped used vehicles, and emissions from electricity production. Using 2002-2020 passenger vehicle registrations data, we document features suggesting that stock turnover has slowed down over time. We then build a stock turnover model to assess how this finding and expected electricity grid decarbonization affect future paths of greenhouse gas (GHG) reductions. We find that at current rates of stock turnover, only moderate GHG reductions are likely by 2030, but large reductions are possible by 2050. This result is robust to a range of assumptions for future grid decarbonization, which has surprisingly little effect on future passenger vehicle emissions. Our results motivate designing policies to accelerate stock turnover for the purpose of achieving near-term decarbonization targets.

Introduction

To address the growing threat of climate change, the United States has established a goal for reducing its own greenhouse gas (GHG) emissions over the current decade. In 2021, the Biden administration announced a goal of reducing economy-wide net emissions by 50-52% in 2030 relative to 2005 levels, which is equivalent to a 43% reduction relative to 1990 levels (White House 2021a). This goal shares a similar ambition to the goal in most recent IPCC report for limiting warming to 1.5 degrees C, which requires reducing global emissions by 40% below 1990 levels by 2030 and net-zero emissions by 2050 (White House 2021b).

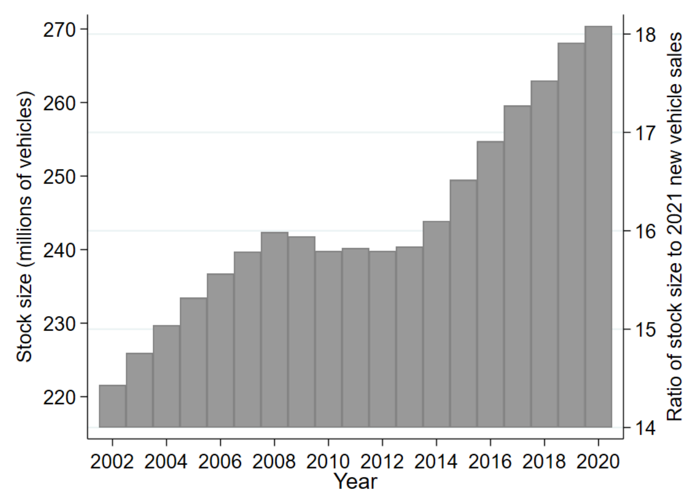
The transportation sector represents the largest source of greenhouse gas (GHG) emissions among all sectors in the US, with passenger vehicle emissions representing the largest share of transportation emissions (EPA 2022a, EPA 2022b). Achieving cuts in GHG emissions necessary to meet the US goals therefore requires substantial emissions reductions from passenger vehicles. Transitioning the fleet to electric vehicles (EVs) is regarded as one of the most promising methods for reducing passenger vehicle emissions. Since EVs emit zero tailpipe emissions, if every vehicle on the road was an electric vehicle and if electricity used to power them were from clean sources, a stock of 100 percent EVs would imply zero passenger vehicle GHG emissions.

This transition, however, critically depends on the replacement of the passenger vehicle stock with new vehicles, which we denote as stock turnover. Each year, on average about 15-17 million new passenger vehicles are sold and enter the vehicle stock of approximately 270 million vehicles and used vehicles are scrapped due to mechanical failures or being totaled in a traffic accident. These two features – the rate at which new vehicles enter the stock and the rate at which used vehicles exit the stock – define how quickly the vehicle stock is replaced by new vehicles. The slower the rate of stock turnover, the longer it takes to transition the stock to 100 percent electric vehicles. Recent modeling has relied on historical estimates of stock turnover that overstate the current rate (Challa et al., 2022; Alafarj et al., 2020; Spangher et al., 2019; Hill et al., 2019).

We document that stock turnover has been slowing down over the last decades, continuing a long-term trend (Hamilton and McCauley, 1999 and Dupor, 2019). One indication of slowed stock turnover is that the average age of passenger vehicles has been increasing over time. According to our passenger vehicle registration data, the average age among all vehicles registered in 2002 was about 8.5 years. This average age increased to just above 11 years old by 2020 (Ferris 2021).

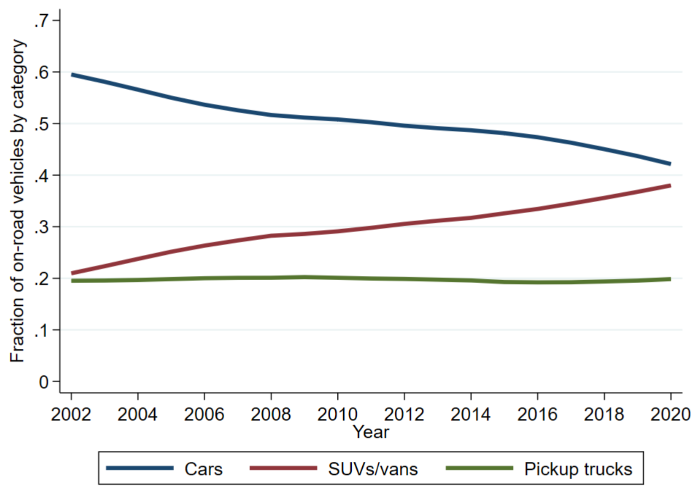
Figure 1 provides an illustration of the slowdown in stock turnover by plotting the number of registered passenger vehicles and the ratio of on-road vehicle registrations to 2021 new vehicle sales. Since 2002, the passenger vehicle stock has grown by about 26 percent, from 216 million to about 270 million by 2020. The larger stock size contributes to a slowdown in stock turnover. For the number of new vehicles sold in 2021 (approximately 15 million units), it would take 14.4 years to accumulate enough sold new vehicles to replace the entire 2002 stock of 216 million used vehicles (216/15 = 14.4). In contrast, it would take 18 years to accumulate enough sold new vehicles to replace the 2020 stock of 270 million vehicles (270/15 = 18).

Figure 1. The number of registered passenger vehicles and the ratio of registered vehicles to 2021 new vehicle sales



Another feature that explains the slowdown of stock turnover is that new vehicle market shares have moved toward SUVs and vans over the last two decades (Harto et al. 2019). SUVs and vans tend to last longer than passenger cars. In 2019, the registration-weighted average scrap rate for cars was about 7 percent; the scrap rate in the same year for SUVs and vans was around 5 percent. As such, a greater number of new SUVs and vans entering the vehicle stock has reduced the rate of which the vehicle stock turns over. Figure 2 plots the share of each vehicle category all vehicles on the road between 2002 and 2020. In 2002, the share of vehicles on the road that were passenger cars and SUVs and vans was 60 percent and 20 percent, respectively. By 2020, the share of passenger cars and SUVs and vans were both about 40 percent each, representing a vastly different composition of body styles in operation.

Figure 2. The fraction of the passenger vehicle stock that is of a certain body style, 2002-2020



The statistics that we document – the increase in vehicle age, the growing size of the on-road vehicle stock relative to new vehicle sales, and the shift in the on-road stock toward SUVs that tend to last longer than cars – together lead to the patterns of an aging stock and a slower rate of stock turnover. To understand the implications of this change in stock turnover for decarbonizing passenger vehicles, we build a stock turnover and GHG emissions model. Our stock turnover model is calibrated to alternative scrappage schedules based on prior studies and a robust set of assumptions for vehicle scrappage in the spirit of Keith et al. (2019). We merge data on vehicle characteristics such as fuel economy, battery range, vehicle miles traveled, and electricity grid CO2 emissions to project annual greenhouse gas emissions for each year between 2021 and 2075.

Results

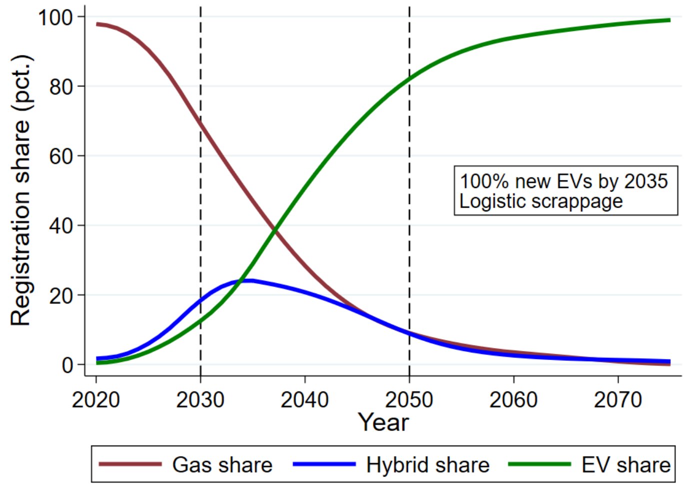
We simulated the stock turnover model to create a series of projections of greenhouse gas emissions between 2021-2075. We consider two key pathways for new vehicle sales: one where the market share for new electric vehicles reaches 100 percent by 2035, and another where the market share for new electric vehicles reaches 75 percent by 2035 and 100 percent by 2045. We chose the 100 percent by 2035 scenario because several large automakers including Ford and General Motors have made public announcements of their plans to phase out gasoline vehicle sales by 2035 and California regulators have proposed a Zero Emission Vehicle (ZEV) mandate scheduled to ban the sale of gasoline and diesel vehicles by 2035 (Becker 2022). We chose the 75 percent by 2035 scenario because various industry sources forecast this rate of EV adoption Muratori et al. 2021). In each scenario, we assume an initial growth in hybrid vehicles followed by a phaseout of hybrid vehicles, based on recent statements made by automobile manufacturers (Jin 2022).

We simulated the stock turnover model under these alternative scenarios to project changes in stock composition. In Figure 3, we plot fuel type registration shares, defined as the number of registered vehicles of a particular fuel type divided by total stock size. Panels (a) and (b) show how registration shares evolve when the new EV market share reaches 100 percent by 2035. The on-road share of EVs reaches about 30 percent by 2035 and continues increasing to about 80 percent by 2050. In this scenario, by 2028 manufacturers begin to phase out hybrid vehicles, which are completely phased out by 2035 as the new EV sales share reaches 100 percent. Therefore, the stock of hybrid vehicles increases and peaks around 2033 and gradually falls toward zero as used hybrids become scrapped over time. The gasoline vehicle stock gradually falls initially, reducing to 80 percent by 2030, then rapidly falls afterwards.

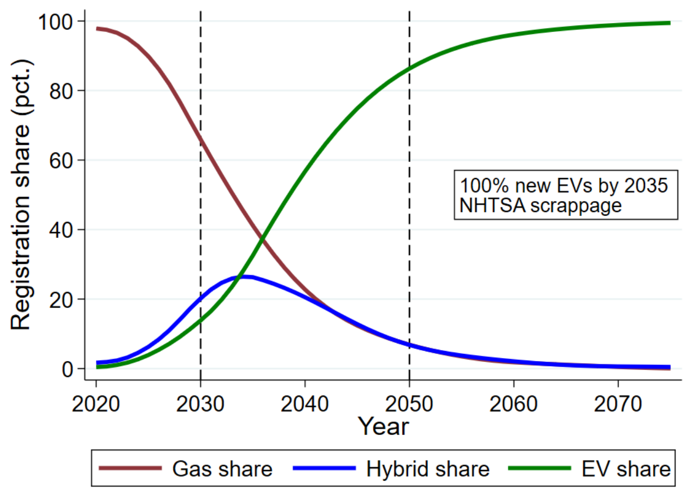
Panels (c) and (d) in Figure 3 show the evolution of fuel type shares for the scenario where the new EV market share reaches 100 percent by 2045. In this scenario, hybrid vehicle sales increase until around 2035, when they begin to be phased out and replaced by EV sales. Therefore, we see the hybrid stock peaking around 40 percent in 2040, then gradually falling after that year. The stock of electric vehicles takes longer to increase, hitting a 50 percent market share in 2045.

Figure 3. Registration shares for alternative scenarios

a.



b.



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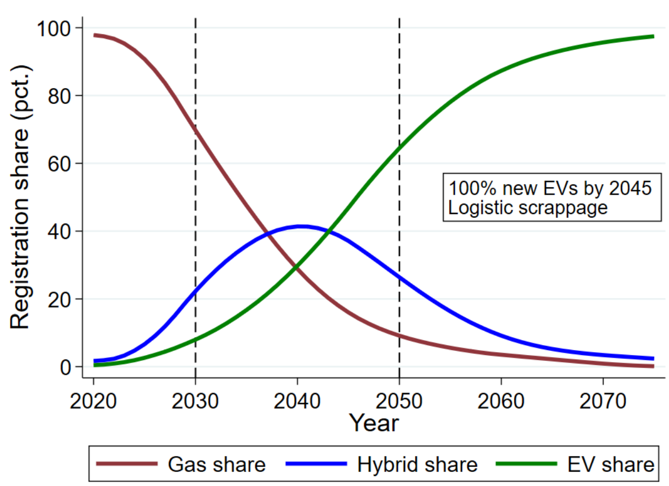

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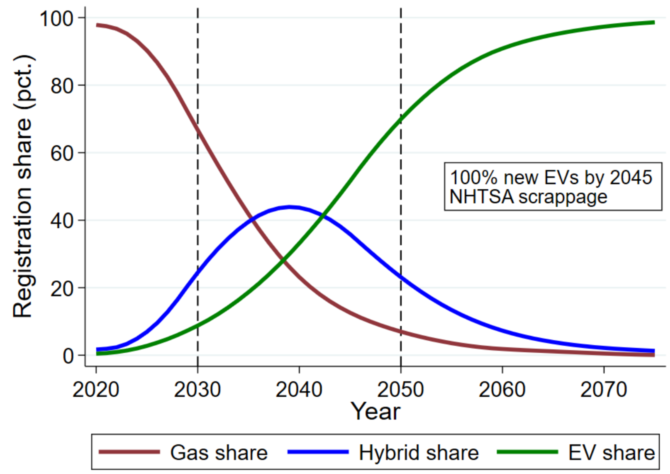
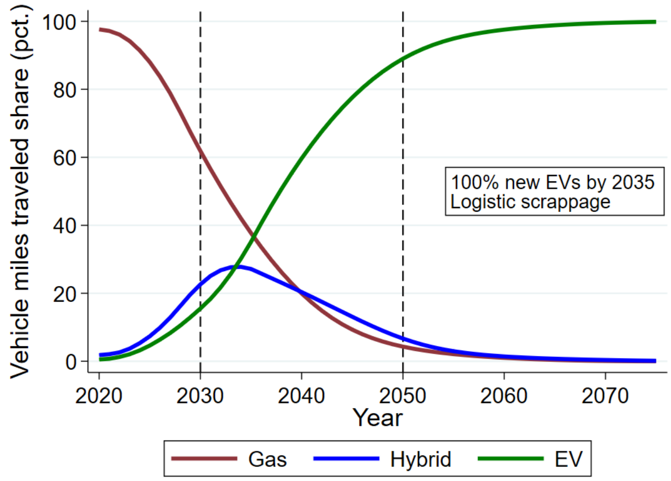


Notes: In each figure, the vertical axis measures the registration share of on-road vehicles for each fuel type. Registration shares are calculated as the number of registrations of a particular fuel type divided by total registrations and sum to one. The EV share includes both plug-in hybrid vehicles and battery-electric vehicles. The horizontal axis represents the year of the simulation. Panels (a) and (b) include assumptions for new EV sales to reach 100% market share by 2035. Panels (c) and (d) include assumptions for new EV sales to reach 100% market share by 2045. Panels (a) and (c) use scrap rate schedules reflecting 2019-2020 scrappage data. Panels (b) and (d) include assumptions for static scrap rate schedules obtained from the NHTSA rulemaking database.

Figure 4 shows changes in vehicle miles traveled (VMT) aggregated by vehicle fuel type as a percentage of total VMT. While this figure looks qualitatively similar to Figure 3, its key distinction is that the VMT shares for EVs approach 100 percent faster than the registration shares. In panel (a), VMT among EVs reaches 90 percent of total VMT by 2050. In panel (a) of Figure 3, the share of EVs on the road is projected to be 80 percent. The reason that VMT share approaches 100 percent faster is that new vehicles tend to be driven more than used vehicles and the stock transition to electric is defined by a rapidly rising EV new vehicle market share.

Figure 4. Vehicle miles traveled shares for alternative scenarios

a.



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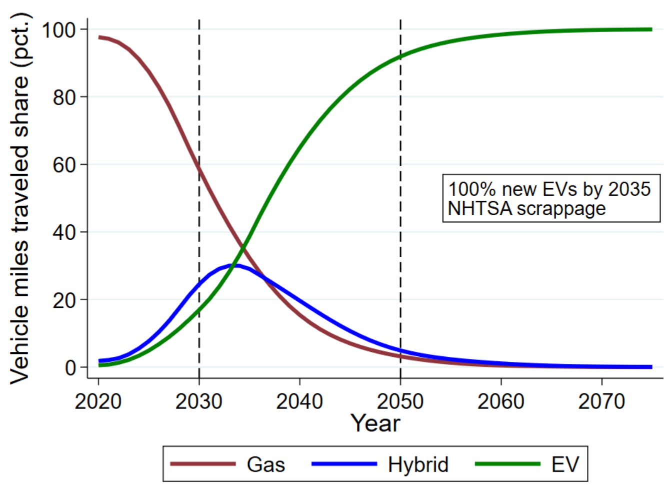

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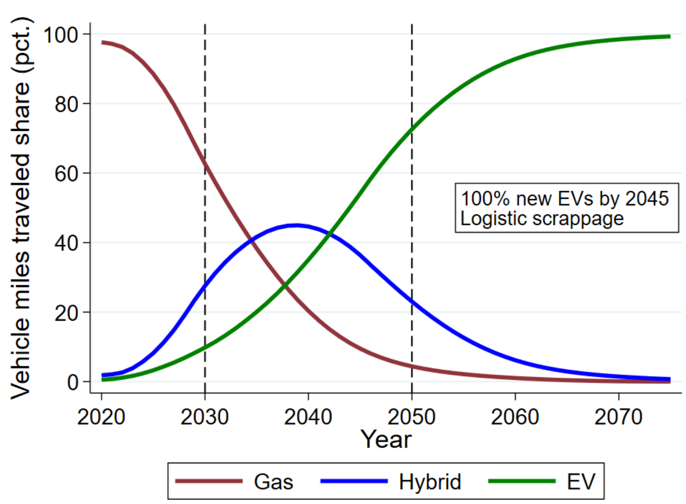

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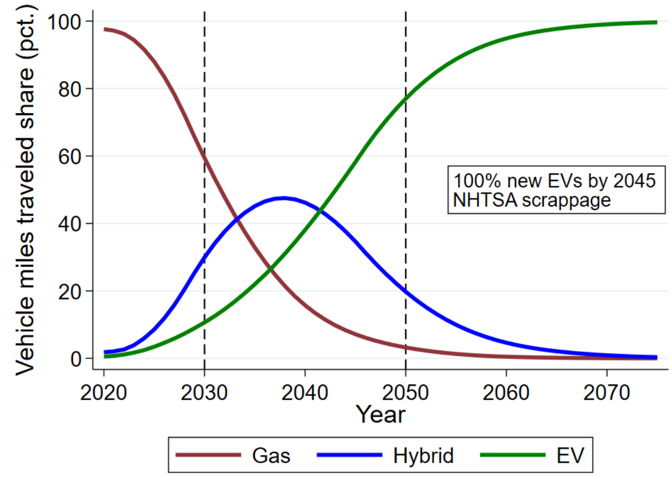


Notes: In each figure, the vertical axis measures share of vehicle miles traveled (VMT) of on-road vehicles for each vehicle fuel type. VMT among the EV group includes VMT of both plug-in hybrid vehicles and battery electric vehicles. The horizontal axis represents the year of the simulation. Panels (a) and (b) include assumptions for new EV sales to reach 100% market share by 2035. Panels (c) and (d) include assumptions for new EV sales to reach 100% market share by 2045. Panels (a) and (c) use scrap rate schedules reflecting 2019-2020 scrappage data. Panels (b) and (d) include assumptions for static scrap rate schedules obtained from the NHTSA rulemaking database.

We present our main findings for CO_2 reductions in Figure 5. This figure contains a range of assumptions for scrappage rates, new EV sales, and grid decarbonization. We consider three scenarios for grid decarbonization: a 95% reduction in carbon dioxide (CO_2) per kilowatt hour (KWH) by 2035 relative to 2020, a 95% reduction in CO_2 per KWH by 2050, and a 65% reduction in CO_2 per KWH by 2050. The plots show percentage changes in CO_2 emissions relative to 2020. In Panel (a), we present results where we use estimated logistic scrap rates and assuming the sales share for EVs reaches 100 percent by 2035. Several key takeaways emerge from the figure. CO_2 emissions fall by about 20-25 percent in 2030 (as indicated by the left vertical dashed line) relative to 2020 levels. Because of rate of stock turnover, in 2030, a large percentage of passenger vehicle emissions are baked in as gasoline vehicles remain on the road for many years, which is why we see only a moderate amount of emissions reductions by then (Hill et al. 2019; Challa et al. 2022).

By 2050, we project that the stock will have had a sufficiently long enough time to turn over to achieve substantial emissions reductions of about 75-85 percent relative to 2020. This result is consistent with Wissell et al. (2022) for scenarios with a nationwide EV policy, whereby the market share of passenger EVs reaches 100 percent by 2035. By this date, a majority of the 2020 stock has been replaced by new vehicles, where an increasing share of these vehicles are EVs.

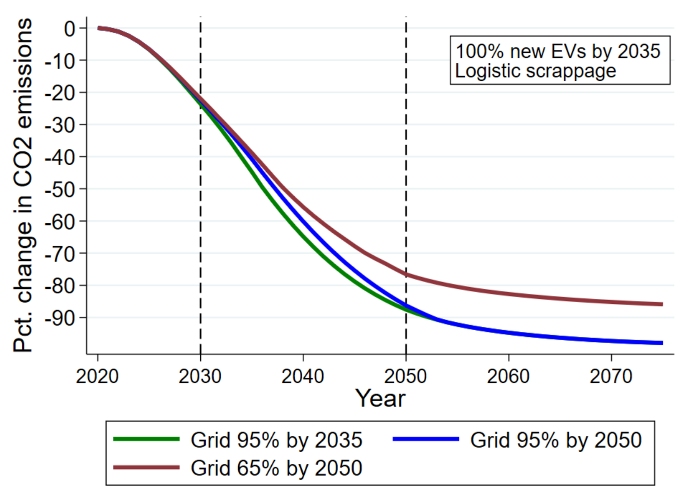
Future grid decarbonization does not appear to have a significant effect on passenger vehicle emissions reductions for the range of scenarios that we consider. According to Panel (a) in Figure 5, this is clearly the case for 2030, where the projected reductions are nearly overlapping at around 20-25 percent. In 2030, EVs have not had much time to percolate through the vehicle stock. Beyond 2030, grid decarbonization matters but only for the slow grid decarbonization scenario. This is because gasoline vehicles remain a significant share of stock, even during 2030-2040 (see Figure 3). The on-road share of EVs picks up significantly just as grid decarbonization kicks in for all three grid decarbonization scenarios. The timing creates an interaction between the evolution of the vehicle stock and electricity grid emissions intensity, where grid decarbonization have only a minor effect on passenger vehicle emissions.

These results are robust to alternative assumptions about projections of EV sales and scrap rates. In Panel (b) of Figure 5, we show projections where the new EV sales share reaches 100 percent by 2035 and using NHTSA database scrappage curves. Emissions reductions by 2030 are about 33 percent in this scenario, which is significantly more than those seen in Panel (a). The NHTSA rulemaking static scrappage schedules lead to faster stock turnover, which accelerates the rate at which old gasoline vehicles are removed from the stock. Therefore, we see greater short-run emissions reductions in this set of projections. By 2050, emissions reductions are 80-90 percent, which is similar to the results presented in Panel (a). By this year, the stock will have had enough time to nearly completely turnover for either assumed set of scrappage schedules; therefore, emissions reductions in Panels (a) and (b) by 2050 are similar.

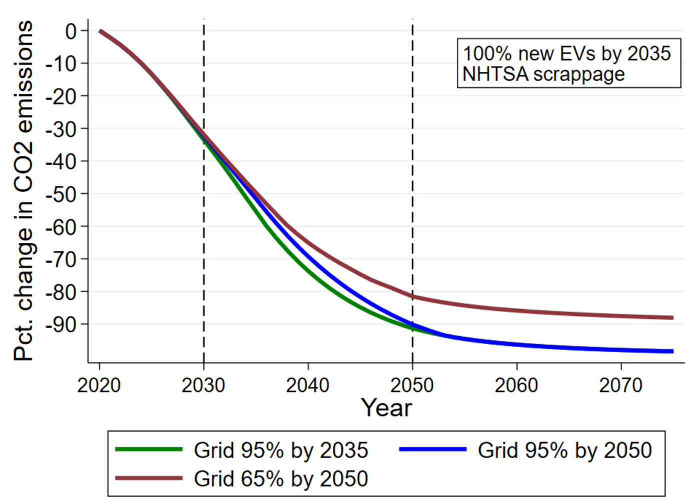
In Panels (c) and (d) of Figure 5, we show projections where the new EV sales share reaches 100 percent by 2045. By comparing Panel (c) with Panel (a), we see that the new EV sales share assumption has little effect on 2030 emissions reductions. By 2050, projected reductions are expected to be 70-80 percent, which is slightly less than those seen in Panel (a). The 10-year delay in achieving a 100 percent new EV sales share still provides the stock with enough time to retire old, fuel-inefficient gasoline vehicles by 2050. Furthermore, the initial increase in hybrid vehicle sales in this scenario helps to lower the gap in emissions reductions between the two scenarios (see Figure 3).

Figure 5. Emissions reductions for alternative scenarios

a.



b.



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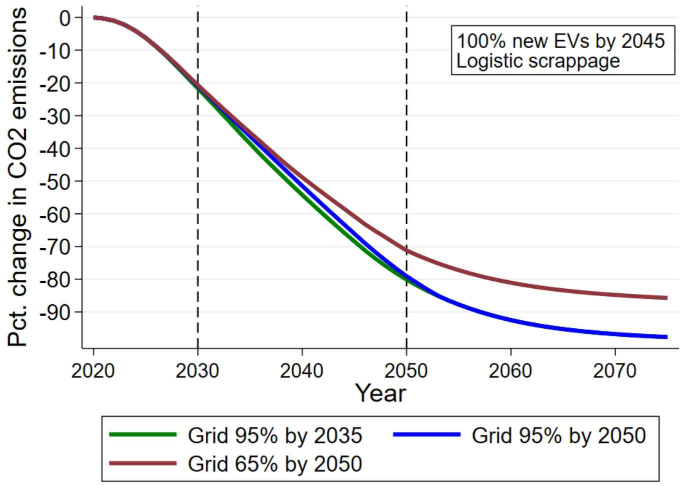

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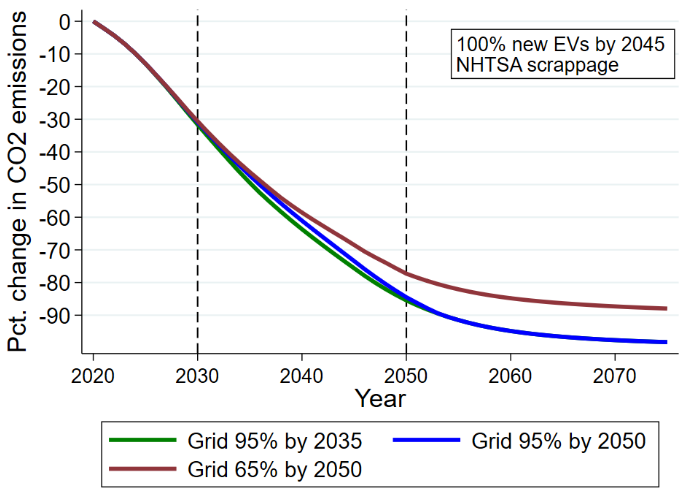


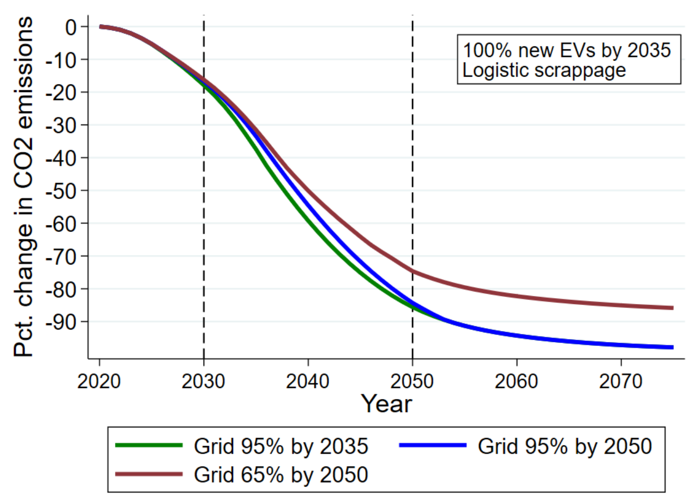
Notes: In each panel, the vertical axis measures the percentage change in CO2 emissions relative to the year 2020. The horizontal axis represents the year of the simulation. Panels (a) and (b) include assumptions for new EV sales to reach 100% market share by 2035. Panels (c) and (d) include assumptions for new EV sales to reach 100% market share by 2045. Panels (a) and (c) include assumptions for scrap rate schedules reflecting 2019-2020 scrappage data. Panels (b) and (d) include assumptions for scrap rate schedules obtained from the NHTSA rulemaking database. The green lines indicate the future pathway for electricity grid decarbonization where the grid achieves a 95% reduction in CO2 per KWH by 2035 relative to 2020. The blue lines indicate the future pathway for electricity grid decarbonization where the grid achieves a 95% reduction in CO2 per KWH by 2050 relative to 2020. The red lines indicate the future pathway for electricity grid decarbonization where the grid achieves a 65% reduction in CO2 per KWH by 2050 relative to 2020.

The importance of hybrids for achieving emissions reductions

Our new vehicle sales scenarios include an initial increase in hybrid sales shares. We explore the importance of this assumption with a series of projections where we assume that hybrid sales shares remain fixed relative to our benchmark year, then are phased out as the EV sales share approaches 100 percent. Figure 6 shows simulation results for this adjustment to our benchmark set of assumptions. Overall, the shape of the emissions paths in Figure 6 look similar to those seen in Figure 5: moderate emissions reductions by 2030 and substantial reductions by 2050. The lack of hybrid growth increases emissions by about 5 percentage points in 2030 relative to the same assumptions in Figure 5. By 2050, the lack of hybrid growth has the largest impact for the scenario where EV sales share reaches 100 percent by 2045 and with our low scrap rate case, which is Panel (c) in Figure 6. In this scenario, emissions reductions reach 60 to 70 percent in 2050, which is about a 10-percentage point difference relative to the same scenario in Figure 5.

Figure 6. Emissions reductions for alternative scenarios, no change in hybrid sales

a.



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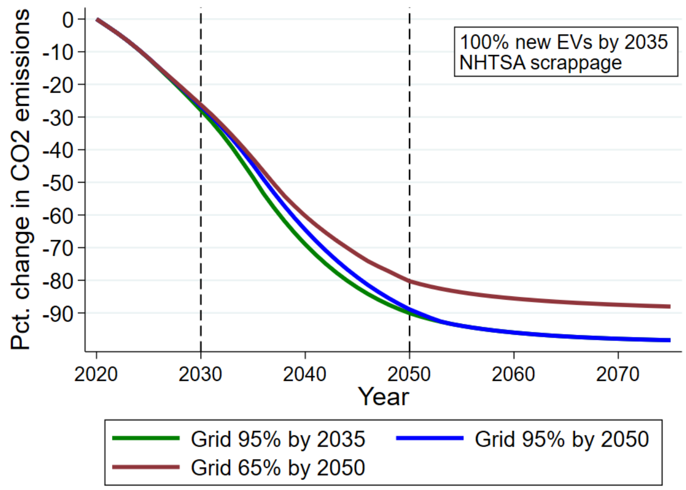

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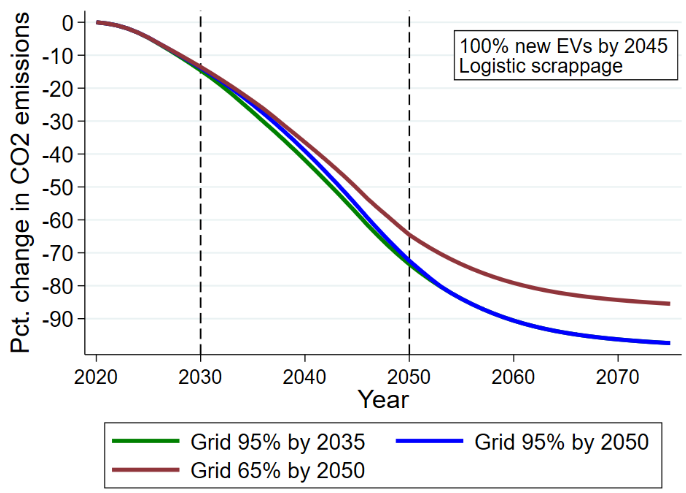

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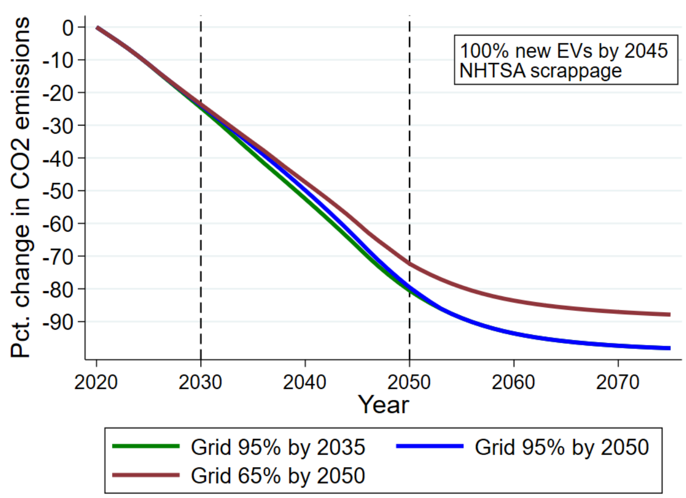

Notes: In each panel the vertical axis measures the percentage change in CO2 emissions relative to the year 2020. The horizontal axis represents the year of the simulation. Panels (a) and (b) include assumptions for new EV sales to reach 100% market share by 2035. Panels (c) and (d) include assumptions for new EV sales to reach 100% market share by 2045. In each scenario, hybrid sales are held fixed at 2020 levels. Panels (a) and (c) include assumptions for scrap rate schedules reflecting 2019-2020 scrappage data. Panels (b) and (d) include assumptions for scrap rate schedules obtained from the NHTSA rulemaking database. The green lines indicate the future pathway for electricity grid decarbonization where the grid achieves a 95% reduction in CO2 per KWH by 2035 relative to 2020. The blue lines indicate the future pathway for electricity grid decarbonization where the grid achieves a 95% reduction in CO2 per KWH by 2050 relative to 2020. The red lines indicate the future pathway for electricity grid decarbonization where the grid achieves a 65% reduction in CO2 per KWH by 2050 relative to 2020.

Discussion

We draw two key conclusions from our analysis. First, at current rates of stock turnover, moderate emissions reductions are likely by 2030. This is primarily due to the slow evolution of the vehicle stock. On the other hand, substantial reductions are possible by 2050 even if new EV sales do not achieve 100 percent market share by 2035; we have shown that a 10-year delay in realizing this goal still achieves large emissions reductions on the order of 70 to 85 percent by 2050. The slow rate of stock turnover has much less of an impact on emissions reductions in 2050, since this time frame appears to be a sufficient timeline to turnover a large majority of the vehicle stock.

Second, our results are surprisingly robust to our range of assumptions for future grid decarbonization, which appears to have little effect on projected passenger vehicle emissions. This is primarily due to the timing of stock turnover. The delay in having a large share of EVs on the road because of stock turnover reduces the magnitude of the effect that grid emission rates have on passenger vehicle emissions. In essence, it is a matter of fortunate timing: the point in the future at which grid emissions rates have fallen significantly is when the share of on-road EVs will be the largest.

Addressing the scrappage component of the decarbonization objective appears necessary to achieve significant emissions reductions by 2030. Current scrap rates suggest that policies such as Senator Chuck Schumer's Clean Cars for America vehicle scrappage subsidy program, is necessary to achieve this target of reductions for the passenger vehicle stock (Clean Cars for America 2019).

Furthermore, large reductions in emissions are attainable as long as new EV sales continue to build and eventually achieve a 100 percent market share within the next few decades. To continue the growth of new EV sales, state and federal subsidy programs are vital to provide sufficient financial incentive for buyers to choose electric over gasoline. Purchase subsidy programs such as a $12,500 vehicle purchase subsidy outlined in President Biden's Build Back Better plan can push more consumers toward EV adoption in the current decade to achieve long term US climate goals.

Methods

We merge several datasets for our analysis. The primary data are passenger vehicle registrations from IHS Market. These data are annual counts of vehicle registrations in the US, where counts are tabulated at the national level and are recorded in the first quarter of each calendar year. In the raw data, we observe detailed vehicle identifiers, including the model year, make, model, trim, fuel type, drive type, body style, and engine size. We observe registration counts for every calendar year between 2002 and 2020.

We merge the count data with fuel economy and electricity use per mile data from Wards Automotive and fueleconomy.gov. We merge the energy use data with the registrations using all available vehicle identifiers, including model year, make, model, trim, fuel type, drive type, body style, and engine size. To assign gasoline and electricity use for plug-in hybrid vehicles, we apply utility factors from the Society of Automotive Engineers (SAE) J2841 database.

We aggregate these counts and energy use to the calendar year-model year-fuel type-body style level by summing the detailed nameplate level counts and taking a registration-weighted average of fuel economy and electricity per mile. We aggregate counts over four fuel types: gasoline, hybrid, plug-in hybrid, and electric. For our body style category, we aggregate to three types: cars, SUVs and vans, and pickup trucks.

We assign vehicle ages to vehicles based on calendar year and model year of each observation in the data. We set age equal to calendar year minus model year. We set age equal to zero (representing a new vehicle) for observations where model year exceeds calendar year.

We obtained annual vehicle miles traveled (VMT) schedules from the NHTSA database underlying the most recent analysis of federal fuel economy standards. The data that underpin the schedules are odometer readings from IHS Market. These schedules are functions of vehicle age and are disaggregated by the three body types: car, SUV/van, and pickup truck. We assume that these schedules remain fixed in future years. This assumption does not imply that total VMT remains fixed, since our model allows for changes in the composition of vehicles on the road and VMT schedules show differences across the three body styles.

We obtained electricity generation (denominated in kilowatt hours) and CO2 emissions (tons of CO2) for three future scenarios from the National Renewable Energy Laboratory (NREL) 2021 Standard Scenarios Report (Cole and Carag 2021). NREL describes the scenarios as follows:

"The first (No New Policy) assumes no new carbon policies beyond those in place as of June 2021; the second (95% by 2050) assumes national power sector carbon dioxide (CO2) emissions decrease linearly to 95% below 2005 emissions by 2050; and the third (95% by 2035) assumes national power sector CO2 emissions decline to 95% below 2005 levels by 2035 and are eliminated on a net basis by 2050." p. vii

We computed a projected CO2 rate by dividing CO2 emissions by electricity generation. Since the NREL projection ends in 2050, we project out beyond this year depending on the scenario. For the No New Policy scenario – defined in our set of scenarios as 65% reduction by 2050 – we assume no change in emissions rates after 2050. For the 95% cut in emissions by 2050, we assume that the CO2 emissions rate falls to zero in 2053, following the path of that scenario. Since the 95% reduction in emissions by 2035 scenario already has zero emissions by 2050, we assume that the emissions rate in this scenario stays at zero after 2050.

To convert gallons of gasoline used to CO2 emissions, we use data from the EPA where each gallon of gasoline burned emits 8,887 grams of CO2, which we convert to 0.000887 metric tons for calculating emissions (EPA 2022c).

We assume new vehicle sales increase by 0.1 percent per year, following assumptions in the EIA Energy

Outlook (EIA, 2022, Table 38). We model sales and stocks of plug-in hybrid and battery electric vehicles separately. We assume that new battery electric sales represent 70 percent of all new plug-in hybrid and battery electric sales, which is consistent with 2021 new vehicle market shares.

We make several assumptions about fuel intensity (the inverse of fuel economy) and electricity use per mile projections. We assume that fuel intensity of gasoline and hybrid vehicles falls by two percent per year through 2022, then by four percent per year through 2026. After 2026, we assume that fuel intensity of gasoline and hybrid vehicles falls by 0.1 percent per year (EIA, 2022, Table 40). For electric vehicles, we assume that electricity use per mile falls by 0.5 percent per year. Combined with our sales projections of gasoline and hybrid vehicles, these assumptions are broadly consistent with future fuel economy standards for passenger vehicles.

Scrap rates

Vehicle scrap rates, which are defined as the percentage of a vehicle type that is removed from the on-road stock from one year to the next, are a key element of our stock turnover model. We assign scrap rates using two alternative sets scrap rate schedules. We follow the scrappage literature and use logistic scrappage schedules (Walker 1968; Parks 1977; Greene and Chen 1981; Engers et al., 2009; Li et al., 2009; Kolli et al., 2010; Jacobsen and van Bentham, 2015; Bento et al., 2018). We adopt scrappage schedules based on logistic estimation of scrap rates and vehicle age from Greene and Leard (2022). We use predicted values for 2019 to assign scrap rates. The second alternative set of scrap rates is based on static scrappage schedules estimated by the National Highway and Transportation Safety Administration (NHTSA) obtained from the input data of the rulemaking analysis of federal fuel economy standards (NHTSA 2022). The NHTSA schedule has similar features of scrappage schedules from the mid-2000s (Greene and Leard 2022). Therefore, these two alternatives can be compared to isolate the effect the change in scrappage over time. For both alternatives, we assume scrap rates of 100 percent for vehicles over the age of 50.

Stock turnover equations

We model how the stock of passenger vehicles evolves with a simple set of survivability equations. Denoting $q_{bf}(a,t)$ as the number of registered vehicles of body style b, fuel type f, age a in year t, the stock evolves according to

$$q_{bf}(a+1,t+1) = \left(1 - y_{bf}(a)\right) q_{bf}(a,t),$$

where $y_{bf}(a)$ is the scrap rate of vehicle body style b, fuel type f, age a.

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