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Decarbonizing US passenger vehicle transport under electrification and automation uncertainty has a travel budget

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Abstract

The transportation sector is at the beginning of a transition represented by electrification, shared mobility, and automation, which could lead to either increases or decreases in total travel and energy use. Understanding the factors enabling deep decarbonization of the passenger vehicle sector is essential for planning the required infrastructure investments and technology adoption policies. We examine the requirements for meeting carbon reduction targets of 80% and higher for passenger vehicle transport in the United States (US) by midcentury under uncertainty. We model the changes needed in vehicle electrification, electricity carbon intensity, and travel demand. Since growth in fleet penetration of electric vehicles (EVs) is constrained by fleet stock turnover, we estimate the EV penetration rates needed to meet climate targets. We find for a base case level of passenger vehicle travel, midcentury deep decarbonization of US passenger transport is conditional on reducing the electricity generation carbon intensity to close to zero along with electrification of about 67% or 84% of vehicle travel to meet decarbonization targets of 80% or 90%, respectively. Higher electricity generation carbon intensity and degraded EV fuel economy due to automation would require higher levels of fleet electrification and/or further constrain the total vehicle travel allowable. Transportation deep decarbonization not only depends on electricity decarbonization, but also has a total travel budget, representing a maximum total vehicle travel threshold that still enables meeting a midcentury climate target. This makes encouraging ride sharing, reducing total vehicle travel, and increasing fuel economy in both human-driven and future automated vehicles increasingly important to deep decarbonization.

1. Introduction

Deep decarbonization of human activities is necessary to increase the likelihood of avoiding global temperature increases of greater than 1.5 or 2 °C in this century [1]. The Intergovernmental Panel on Climate Change (IPCC) examined emissions scenarios likely to maintain warming below 2 °C in the 21st century relative to pre-industrial levels. These scenarios are characterized by global anthropogenic greenhouse gas (GHG) emissions reductions of 40%–70% by midcentury compared to 2010 [2]. More recently, the IPCC concluded that reaching net zero CO₂ emissions globally around 2050 would likely be required for limiting global warming

to 1.5 °C above pre-industrial levels [3]. Because of traditionally long infrastructure turnover timelines, the committed emissions from existing energy and transportation infrastructure across sectors would jeopardize meeting this 1.5 °C climate target, without accelerated policy efforts [4]. Deeply decarbonizing the transport sector is an essential element in any climate stabilization scenario, and requires a major transition in energy use, vehicles, and enabling infrastructure [5]. While there is some progress in reducing emissions from electricity generation, emissions from transportation, representing 23% of global energy-related CO₂ emissions, continue to grow [2, 6]. The transportation sector is at the beginning of an age of ‘advanced mobility’ represented by

electrification, advanced mobility, and automation [7]. Electric vehicle (EV) cost declines, IT-enabled vehicle ridesourcing, public and personal transport innovations, and partial and full personal vehicle automation systems will fundamentally change transportation. These technologies could improve efficiency, affordability, mobility, and accessibility, however the impacts of these technologies on total travel, energy use, and emissions remain uncertain [8–14]. Thus, any decline of transportation emissions is dependent on use, deployment, and importantly, electricity emissions. Still, transportation deep decarbonization by midcentury under the uncertainty that advanced mobility brings requires policy actions, and identifying robust pathways to achieving climate policy objectives.

The US transport sector represents about 33% of total US CO₂ emissions, approximately 1800 million metric tons [15]. Light-duty vehicles (LDV) comprised of passenger cars and light trucks are responsible for about 60% of these transport emissions [15]. The US Energy Information Administration (EIA) projects that due to increases in vehicle efficiency and about a 12% penetration of EVs, mostly Battery Electric Vehicles (BEVs), total US transportation sector CO₂ emissions in 2050 will be slightly less than current levels, despite a total passenger vehicle travel increase [16]. This is due to the improved fleet average fuel economy which EIA projects to increase by more than 60% by 2050, driven by the penetration of alternative fuel vehicles and overall technology advancement [16]. While these projections do not consider the impact of future policies and may underestimate technology advancement, achieving deep US GHG emissions reductions by midcentury will still require much larger changes in the transportation sector [17, 18].

As the LDV fleet represents the majority of transport demand, energy use, and emissions [16], potential modal shifts away from personal vehicles to public and active transport should be one of the strategies for transport GHG reduction. However, the growth of shared mobility through ridesourcing and vehicle automation may increase public transit use through providing last and first mile accessibility [19], or result in a modal shift from public transport to passenger vehicles [12], or a combination of these effects. Therefore, a robust strategy for deep decarbonization under technology and behavioral uncertainty must address LDVs as a primary component. While there are aggressive transition projections to achieve GHG reductions in the LDV sector [20–27], the incumbency of vehicle and refueling technologies as well as the time required for fleet compositional changes can constrain options and strategies. Potential alternative fuels include hydrogen made from low-carbon sources used in fuel cell vehicles, advanced low-impact biofuels, and carbon neutral hydrocarbons (CNHCs) that re-use CO₂ extracted

from the atmosphere via biomass use or direct air capture and hydrogen from carbon-free sources to create to a useable fuel. All of these fuels are under development with known and unknown challenges to overcome that include cost, infrastructure, land use, and uncertainty in life cycle emissions [28–34]. What remains is electricity, which has the ability to use a variety of existing low-carbon technologies for generation and distribution such as wind, solar, hydro, and nuclear, providing a diverse portfolio of clean energy sources that could ensure a reliable and low cost transition to a near-zero emissions grid [35]. It is therefore, the independent pace and scale of both vehicle electrification and electricity decarbonization that will ultimately determine the energy and environmental outcomes of the transportation sector through 2050.

In 2018, the global EV stock exceeded 5.1 million, and close to 2 million new EVs were sold worldwide [36]. But EVs remain a small percentage of new sales (2.2%) and the total fleet of vehicles (0.43%) [36, 37]. China, the US, and Europe comprised over 90% of global EV stock [36]. Policy incentives can increase the pace of a transition to EVs. In 2017, China announced a policy to phase out production and sales of conventional fossil fuel-powered vehicles [38, 39]. This policy in the world's second largest economy and largest auto market has considerable implications for the global oil market, the automobile industry, and the rate of EV technology penetration and advancement. India and many European countries such as France, the United Kingdom, and others have discussed setting targets to phase out sales of gasoline and diesel vehicles [39].

Along with vehicle electrification, advanced mobility services represented by the emergence of individual and shared ridesourcing offered by Transportation Network Companies (TNCs) such as Uber and Lyft, as well as potential vehicle automation, could reshape passenger transport [7, 12]. TNC options could increase ride sharing, but also could increase total vehicle kilometers traveled (VKT) (or vehicle miles traveled (VMT)) or shift demand away from public transit [12, 40]. Partial and full vehicle automation could offer synergies with electrification, and could either increase or decrease fuel economy, vehicle travel, and energy use, depending on how these vehicles are deployed and used [10, 11, 41–43]. However, coupling an increase in shared ridesourcing with electrification and optimizing automation strategies to reduce vehicle travel and energy use could increase the likelihood of meeting climate mitigation targets [7]. LDV transport deep decarbonization under advanced mobility will depend in part on this total travel demand, which represents a mitigation frontier of what is possible in the next few decades.

It is critical to characterize and manage uncertainties across the multiple facets of the

electricity and transport systems when analyzing decarbonization pathways [44, 45]. Here we assess the bounds of EV adoption, the pace of electricity decarbonization, and total travel demand for decarbonizing the US LDV sector to achieve GHG emissions reduction targets by 2050. For the base case, we use an 80% reduction by 2050 compared to emissions in the reference year of 2005—a common midcentury decarbonization benchmark target [17, 45]. We also examine a 90% reduction target to understand the sensitivity of decarbonization requirements to this policy goal. To enable comparisons with national projections, inventories, and other studies, we only include direct CO₂ emissions and exclude life cycle impacts [15, 16]. We include CO₂ emissions from electric power generation units for the EVs and fuel use for internal combustion engines, but not upstream impacts from producing fuels, vehicles, and batteries, which are assessed in other studies and introduce additional model and scenario uncertainties [46, 47], although we comment on the life cycle implications in the discussion section. Similar to a robust decision making approach [48], we assess the conditions that enable meeting a mitigation target (e.g. an 80% reduction in 2050) for the passenger vehicle transportation sector by understanding the factors affecting deep decarbonization. This enables public and private stakeholders to make choices on the required enabling infrastructure, investments, policies, and technologies.

2. Method and data

We considered the 1134 million metric tons of CO₂ from 2005 US LDV travel as a reference value [15]. Reducing the 2005 value by 80% results an emissions target of 227 million metric tons in 2050 [15], and we use 250 million metric tons to simplify the analysis and visualization. For a more aggressive target of 90% reduction, the target would be 113 million metric tons, and we use 120 million metric tons as an approximate target. Our results can also assess reaching a 100% reduction target, which requires a zero GHG electricity sector and full vehicle electrification. However, it is important to stakeholders to understand the

implications of the 80% and 90% reduction targets to enable policy planning under uncertainty.

In order to characterize the requirements to reduce US LDV CO₂ to 250 and 120 million metric tons in 2050, we model: the share of LDV travel from EVs, the carbon intensity of electricity, the fuel economy of EVs and ICEVs, and the total travel from LDVs using equation (1). Using this equation with EIA reference case projections resulted in comparable CO₂ emissions to EIA's (See Supporting Information (SI) tables S1–S7 and calculations). Ranges of possible values for these variables are used to find combinations that meet the target emissions in 2050. The US electricity carbon intensity (CI) has decreased by about 30% since 2001 and is expected to further decrease with a continued shift from coal to natural gas and increased renewables [49, 50]. The EIA's projected vehicle travel in 2050 is about 3.3 trillion miles (or 5.28 trillion km) [16]. In this paper, we use VMT instead of VKT in order to be consistent with US regulatory agency reporting. All the metrics and their associated units in the analysis are shown in the SI table S1, as well as the calculation of the targets and the current and historical levels of annual LDV CO₂ (table S2) and parameters used (table S3).

Hybrid electric, diesel, and ethanol powered vehicles were modeled as part of the ICEV fleet in addition to conventional gasolines, and their weighted average fuel economy was estimated using EIA's projected 2050 composition of the ICEV fleet [16]. We refer exclusively to BEVs as EVs since they are projected to be the major electric vehicle technology in 2050 (more than 80% of the EV fleet) with the remaining 20% from Plug-in Hybrid Electric Vehicles (PHEVs), hence we provide a conservative estimate of the required travel electrification [16]. We considered ranges for EV adoption represented as the EV share of LDV travel ranging from 0% to 100%. We also considered the charging, transmission and distribution losses in the CO₂ emissions estimation. We assumed an 88% charging efficiency to account for the plug-to-wheels losses [51, 52], and approximately 4.5% for the losses in the power transmission and distribution system [53].

$$TotalLDVCO_2(kg) = \frac{\alpha \times (1 + L) \times totalVKT \times EV_CI \left(\frac{kg}{kWh} \right)}{EV_FE \left(\frac{km}{kWh} \right)} + \frac{(1 - \alpha) \times totalVKT \times ICEV_CI \left(\frac{kg}{l} \right)}{ICEV_FE \left(\frac{km}{l} \right)} \quad (1)$$

where α represents the fraction of the LDV travel by EVs, and $(1 - \alpha)$ represents the fraction that is traveled by ICEVs. Total VKT represents the total km traveled by the LDVs in the US for one year. The loss factor (L)

used was calculated as $(L = 0.12 + 0.045)$ to include the charging and grid inefficiencies.

The EIA projects a 2050 US net generated electricity carbon intensity of 329 g CO₂ kWh⁻¹, and the 2018 level was 428 g CO₂ kWh⁻¹ [16, 50].

This AEO-projected electricity carbon intensity is incompatible with the climate targets under consideration. We focus on lower levels of electricity net generation carbon intensity representing the US national average electricity generation mix, which would be associated with charging EVs in 2050. Urbanization and driving patterns vary by region, as do electricity emissions which also vary by season and time of day. Yet here we model the entire US to illustrate the scale of emissions reductions and fleet technology change required at the national level. EV charging initially represents new demand served by marginal generators. Yet electrifying the vast majority of LDV travel for deep decarbonization will require both the average and the marginal emissions of the generation fleet to be deeply decarbonized. If states such as California continue to make progress on vehicle electrification and electricity decarbonization ahead of other states, this provides some room for other states to increase efforts somewhat more slowly. However, what matters for climate policy is the total amount of CO₂ from the transportation sector, and an 80% or 90% or greater emissions reduction will require a substantial fleet and electricity grid transition across all regions.

The EV and ICEV fuel economy (FE) values represent the weighted average fuel economy of the technology fleet in a given year. The assumed fuel economy value for ICEVs is based on the base case projections of its technology mix (i.e. by blended gasoline, diesel, ethanol, and hybrid) of vehicles in the fleet from the Argonne National Laboratory VISION 2018 Model which uses the EIA's Annual Energy Outlook, as shown in SI table S4 [16, 54]. These fuel economy values are expressed in miles per gallon of gasoline equivalent (mpgge) (and converted to km/l) and represent the weighted average value of the vehicle measured fuel economy based on standardized test cycles. However, these laboratory-measured fuel economy values are generally higher than fuel economy observed in actual vehicle operations. Hence we used a road degradation factor for each technology to better capture real on-road fuel consumption [54]. We use a 2050 EV FE base case level of 6 miles kWh⁻¹ (9.67 km kWh⁻¹) given the ongoing and future technology improvement. We test the sensitivity of the results to this assumption by considering EV FE levels of 3 and 9 miles kWh⁻¹ (4.8 and 14.5 km kWh⁻¹, respectively) as shown in tables S8–S10.

The ICEV CI term is the weighted average combustion carbon intensity (emission factors) of the fuels burned by the ICEVs vehicles in the fleet. The emission factors for the liquid fuels such as gasoline and diesel were taken from the Environmental Protection Agency (EPA) and used to calculate the weighted average CI for ICEVs [55]. We assumed about 12% ethanol content by volume in the 2050 blended gasoline used by conventional cars and light trucks [54]. The EV carbon intensity here is the direct

CO₂ emissions of combustion of fuels for electricity generation.

The LDV survival curves for cars and light trucks from the Transportation Energy Data Book were used to estimate the lifetime of EVs and ICEVs entering the fleet [56]. Overall, our data source for this analysis was the EIA 2018 Annual Energy Outlook (AEO) [16]. The base case values for the projected LDV travel demand (VMT) and future annual sales were all taken from the AEO. Also, the projected base case EV sales and fleet stock from AEO and VISION were used in modeling the fleet turnover [16, 54].

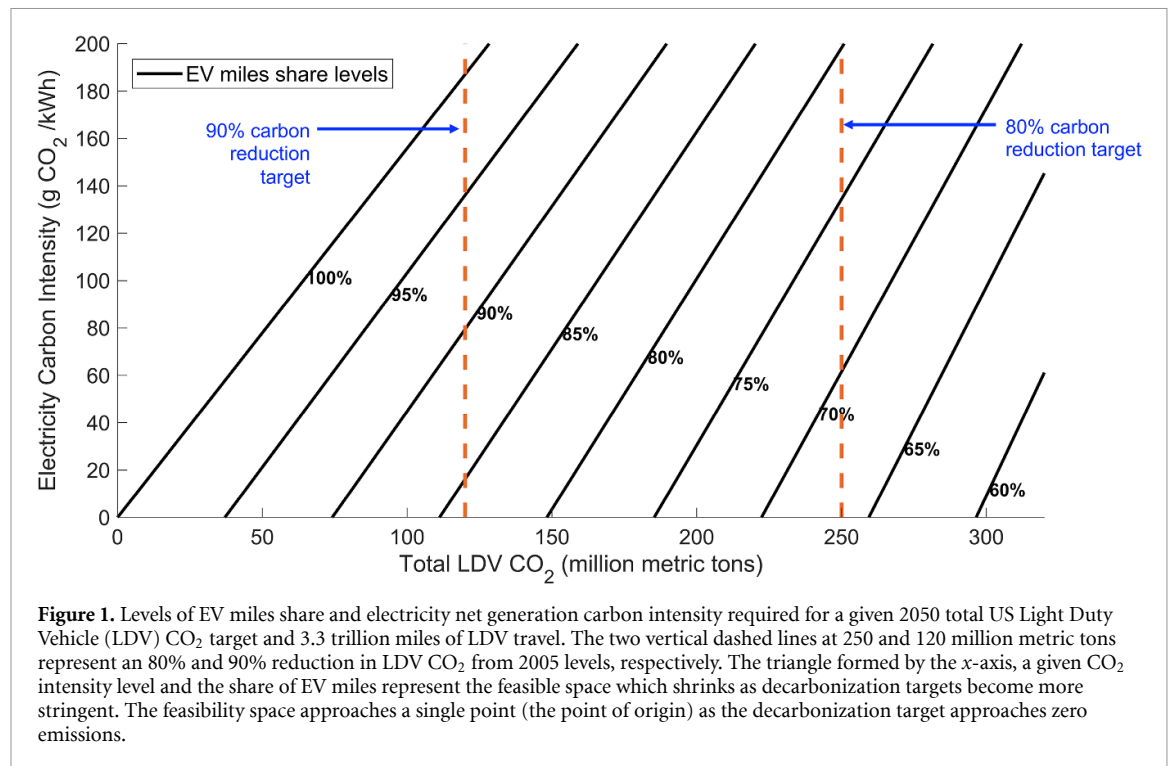
3. Results and discussion

3.1. Meeting a climate mitigation target in transportation

We show in figure 1 a range of possible total US LDV CO₂ emissions in 2050 ranging from zero to 300 million metric tons to illustrate the sensitivity of the results to different decarbonization policy targets. Figure 1 shows the required electricity net generation carbon intensity and EV travel share of the total US LDV miles to meet a given total CO₂ emissions target in 2050. The targets of 80% and 90% reduction from 2005 levels are indicated by the two vertical dashed lines. We find that reducing LDV CO₂ emissions to 250 million metric tons is attainable if the electricity carbon intensity is reduced to zero and about 67% of LDV travel is electrified. For the 90% reduction target, about 84% travel electrification would be needed. These targets could also be met with somewhat higher electricity carbon intensity but would require more electrification of LDV miles. The feasibility space for this trade off shrinks as the climate target becomes more stringent. Ultimately, meeting the IPCC target of net zero CO₂ emissions [3] for LDVs implies zero carbon electricity and full electrification, hence reducing the feasibility space to a single point. Therefore, decarbonizing electricity is the major constraint and opportunity for meeting climate targets through transportation electrification. The 2050 EV fleet average fuel economy assumed in figure 1 is 6 miles kWh⁻¹ given potential future improvements in efficiency, battery specific energy, lighter vehicle weight, and other improvements. However, with the potential additional energy required for vehicle automation (e.g. computing, sensing, additional weight) [43], the EV fleet average FE could be lower. Figure S1 shows how figure 1 would change if the 2050 EV fleet average FE is reduced to 3 miles/kWh.

3.2. The travel budget frontier

Next, we examine the effect of the travel budget frontier, which is the maximum total miles that can be traveled without exceeding the targeted maximum emissions, for a given EV share and electricity carbon intensity. Figure 2 shows the space of the possible combinations of the electricity carbon intensity and



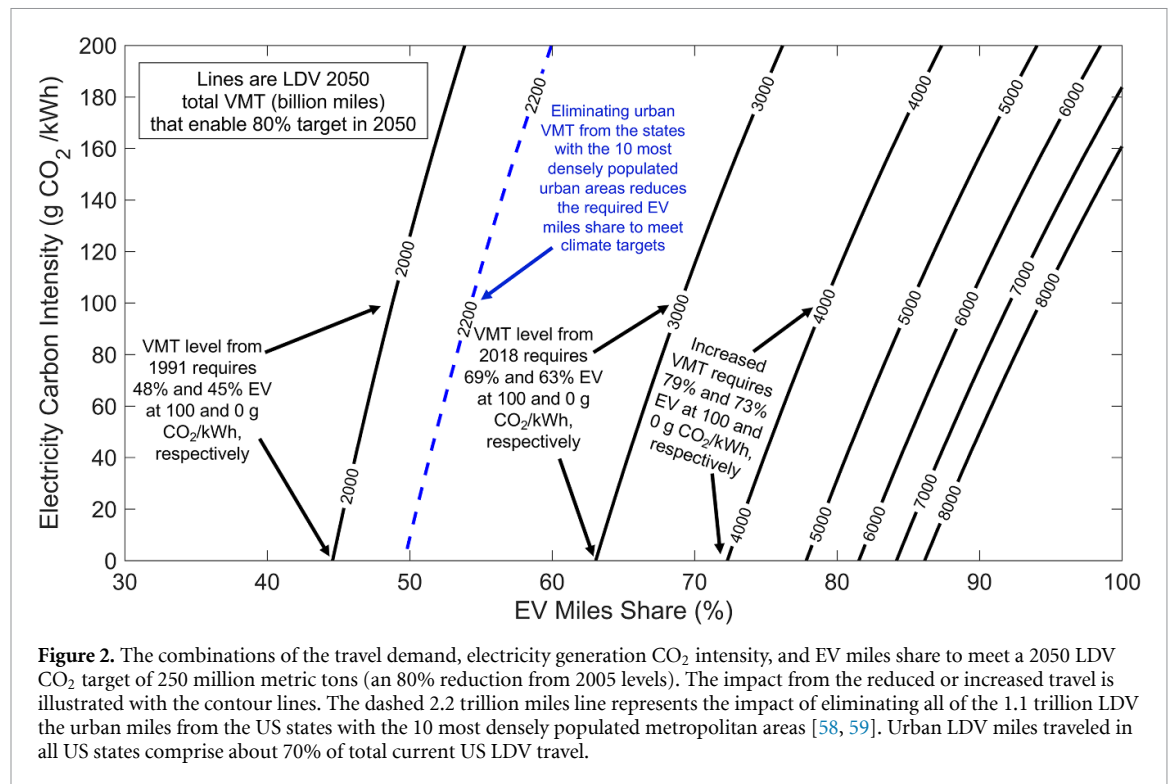
travel electrification that meet the 80% target for different levels of LDV total VMT. Figure S2 shows that the more aggressive 90% target results in increasing the required electricity decarbonization and travel electrification. We emphasize that for a given EV miles share, reducing the electricity carbon intensity stretches the travel budget and increases the maximum total VMT that can be traveled while meeting the target. Behavioral changes can lead to travel demand reductions, but given historical trends and current projections [16, 57] it is prudent to consider cases where total demand does not fall. Assuming no travel demand reduction, there is only a narrow region of EV miles and electricity carbon intensity combinations that can meet the climate target. Further decarbonization of the electric power sector could increase the travel budget or reduce the travel electrification requirement. These findings highlight the window of feasible conditions to meet LDV decarbonization targets, when constrained by the total travel demand. For example, if automation or other factors increase total LDV travel to 4 trillion miles, the minimum EV miles share would increase by about one fifth.

We further examined the effect of an upper limit of 9 miles kWh⁻¹ for EV FE, reflecting a scenario when potential operational effects of connected automated vehicles (e.g. eco-driving, platooning, and intersection connectivity) coupled with improved batteries enhance the average fuel economy of EVs [43]. As tables S8-S10 show, improved FE of EVs, and more importantly limiting any total travel increase (through means of modal shift and shared mobility), hedge against any shortfall from electricity not being

able to achieve zero GHGs by 2050. While the impact of EV FE on the required travel electrification and total emissions becomes irrelevant with zero carbon electricity, improved ICEV FE (50 mpg) can considerably reduce the minimum required EV miles share as shown in SI figures S3 and S4.

There are opportunities to reduce total VMT and associated emissions while maintaining mobility and passenger miles traveled (PMT). These opportunities include shared traditional or automated ridesourcing, carpooling, and lower impact modes such as transit, bicycles, scooters and walking [8, 11–13, 60]. If VMT is reduced through mode shifting and advanced mobility approaches, the possibility frontier of meeting the carbon reduction target expands, and fewer EV miles are required. However, the opposite would occur if advanced mobility technologies result in increased total VMT. For example, reducing VMT to 2 trillion miles in 2050 would require a minimum of 45% EV travel, while increasing VMT to 4 trillion miles results in minimum of 73% EV travel to meet the 80% target as shown in figure 2.

Because transportation CO₂ emissions are directly coupled to total distance traveled, figure 2 addresses the feasibility space for meeting the climate target through decreased VMT, whether through demand reduction (less travel), a shift to transit or other modes, or increased ride sharing (i.e. increased PMT). The long-term historical trends in the US could continue and traditional privately-owned LDV travel could dominate passenger travel while public transit remains a small portion of passenger travel. Previous work also expects a limited contribution to emission reductions from activity reduction and



modal shifting compared to fuel switching and further enhancements in energy efficiency [61, 62].

However, there is an opportunity to reduce and shift US urban LDV VMT, which comprises about 70% of total LDV VMT [58]. Further, urban VMT in the 13 states that have the top ten metropolitan areas in terms of population density, comprise almost one trillion VMT, or one-third of current US LDV VMT (See SI table S11–S13). In figure 2 we illustrate the impact of eliminating this urban VMT on the miles budget (further cases in figure S5), which can help bound the large improvements possible through VMT reduction. Synergy between public transport and shared, automated and connected vehicles, as well as bicycle, scooter, and pedestrian modes could provide mobility that enables PMT while reducing VMT. Shared EVs could be responsible for the last mile delivery of passengers to and from destinations and public transit stops. This means public transit and advanced mobility could serve some of the PMT demand and help meet a climate target under a total travel budget. Shifted miles from LDVs to public transit would still emit CO₂ emissions, whether shifted to rail, conventional buses, or electric buses (with electricity greater than 0 g GHG kWh⁻¹). The additional emissions from these shifted miles, when coupled with LDV emissions, will need to remain below the climate target to prevent emissions leakage from the LDV sector to the transit sector. This highlights the importance of a deeply decarbonized electricity system and electrification of transit modes in addition to electric LDVs. Yet, others did find that achieving large efficiency improvements and fuel

switching makes it possible to meet CO₂ emission reduction targets without large shifts to public and non-motorized transport [63].

Ride sharing impacts can be quantified through an increase in the load factor (LF) of trips, computed as person miles of travel per vehicle mile [64]. The load factor of the US LDV sector was estimated as the VMT weighted average of the load factors for cars and light trucks from the 2017 National Household Travel Survey (NHTS) [64]. The estimated average load factor is about 1.60 based on the recent NHTS, slightly lower than the 2009 level of 1.63 passengers averaged across VMT that was used in previous studies [11] (see SI table S14 for historical values of the load factor) [57, 64]. We note that the NHTS is a survey, and actual load factors may be different both spatially and temporally. To examine the effect of the load factor on meeting the emissions target level, we varied the load factor in our model from 1 to 2.5 as shown in figure 3. Using the EIA projected total VMT for 2050 and the current load factor of 1.60, the projected 2050 PMT would be about 5.3 trillion miles, while the current PMT is about 4.6 trillion miles [16, 57, 64]. We show three cases of high travel electrification and low electricity CI in figure 3. Other combinations including lower EV miles share (50%) and higher electricity CI (100 and 150 g CO₂ kWh⁻¹) are shown in SI figures S6 and S7. In all cases, as load factor increases, total VMT declines while PMT demand is met. Figure 3 shows increase ride sharing enabled by advanced mobility effectively reduces the minimum electricity decarbonization and fleet electrification requirements to meet a climate target. While ride

sharing could increase load factors, increased miles traveled by ridesourcing vehicles cruising between pickups or potentially automated vehicles traveling without a driver could decrease load factors and policies would be needed to reduce cruising and reduce the impact of decreased load factors [8].

3.3. The impact of fleet turnover timelines

The share of EVs in the LDV stock is affected by vehicle turnover, which is constrained by the penetration rate of the new vehicle technology as well as the rates and ages when vehicles exit the fleet (see table S16). New ICEVs that enter the stock will effectively delay a transition to a predominately electrified fleet unless the ICEVs exit early [65]. Stock turnover limitations and the timing of the new vehicle technology deployment will affect total emissions and fuel economy [65, 66]. Additionally, more automated features could likely reduce crashes [67, 68], and also extend vehicle lifetimes and stock turnover time as fewer vehicles retire due to crashes. Based on current LDV survival curves, it takes about three decades for all of the current LDV stock to retire [56]. We show the effect of EV penetration rate and stock turnover on meeting the climate target in figure 4. Using current projected rates of total vehicle sales and retirements, getting to a 100% EV fleet in 2050 requires all LDV sales to be only EVs starting in 2020. To find the year when all LDV sales need to be EVs to reach a specific stock share in 2050, we conservatively examine if the sales of EVs follow the EIA reference case trajectory and vary the starting year of 'only EV' sales until the target level is met. Since about 67% EVs is the minimum EV share that can meet the 80% climate target with decarbonized electricity without reducing projected baseline VMT (See figure 2), the lower bound case shows that 2040 is the latest possible year to start EV only sales and reach 67% EVs by 2050. For the 90% target, 2037 would be the starting year for selling only EVs to reach about 80% EVs in the fleet by 2050. We include additional hypothetical cases for the starting years that would be required to meet the Bloomberg New Energy Finance (BNEF) 2019 Electric Vehicle Outlook projection of 42% EVs in the US in 2040 [69]. These results also highlight the effect of the long tail of the vehicle survival curve, as it takes more time to retire the last 10% of the replaced technology [56] and the likely need for policies to induce the early retirement of petroleum-powered vehicles. Considering that new vehicles are on average driven more than older ones, the targeted travel share could be reached earlier than the physical stock share of vehicles. We used a typical annual miles by age distribution [54] for passenger cars and light trucks to calculate the difference between the miles share and stock share. As shown in figure S8, the miles share always exceeds the stock share and the annual difference can be up to 7%, depending on the number of years since starting to sell only EVs. This indicates the

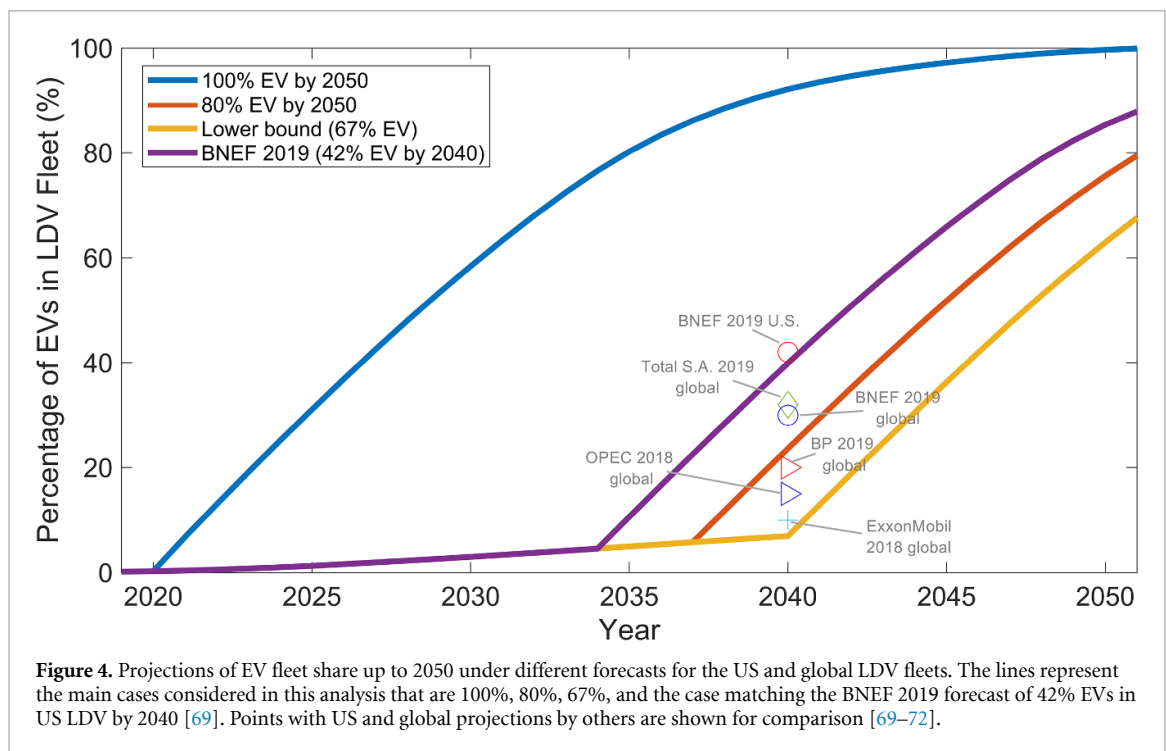
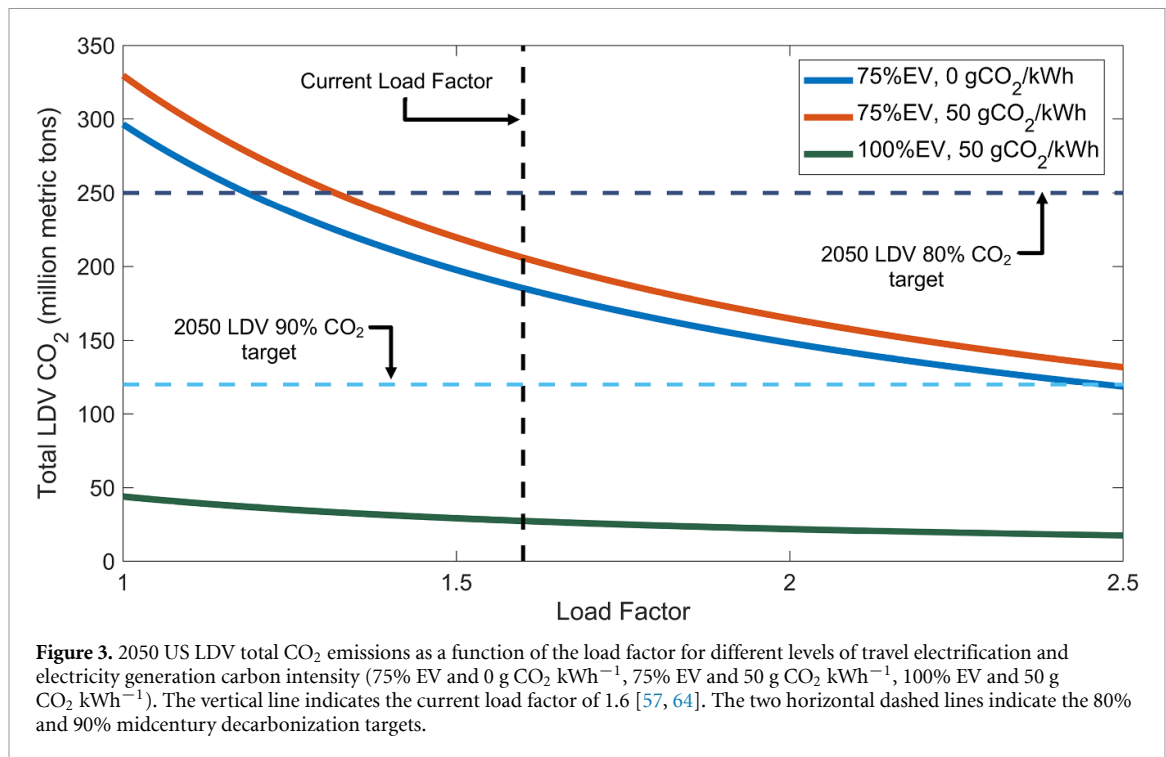
benefit of early introduction of EVs at large market shares along with targeting higher utilization of EVs and designing policies to decrease the average annual miles driven by ICEVs.

Further, the high EV travel share required to meet the decarbonization target can be met with an even lower stock share through increasing the utilization of those vehicles beyond the annual miles of typical new vehicles. For example, a vehicle stock that has 50% EVs could have considerably greater than 50% of annual travel by EVs, if these EVs are highly utilized (i.e. driven more over the year than the annual LDV average). Figure S9 shows the impact of decoupling the EV travel share from the EV fleet share. High utilization of the EV fleet could effectively offset some of the fleet electrification requirement for meeting transport carbon reduction targets. Thus, vehicles with high utilization rates such as taxis, ridesourcing vehicles, and service fleets could be the early adopters of EVs during the transition and can accelerate the climate benefits, but this would require carefully designed policies such as additional subsidies for highly utilized EVs, EV-only access zones in urban areas, or other incentives for EV ride sharing or fees for single occupancy vehicles in urban zones.

The potential of high EV utilization through ride sharing despite low EV fleet share could also be constrained by the spatial and temporal distribution of passenger demand. It will likely require higher capacity EV shuttles in dense urban areas. In the suburbs, exurbs, and rural areas, the density of the demand is much lower, and trips are usually longer, thus reducing the opportunities for ride sharing and increasing the need for focused policies. Despite these challenges, given the increased urbanization and advancements in vehicle automation, and ride sharing optimization by TNCs, the urban areas might be able to partially offset limited ride sharing in other areas. Urban areas currently comprise about 70% of total miles of road transport in the US, which is dominated by LDVs [58, 73]. Therefore, urban areas need to achieve higher levels of electrification and ride sharing, to offset a potentially more limited transition in rural areas to reach the targeted load factor, EV travel share levels, and emissions reductions.

4. Pathways for passenger transport decarbonization

We presented the required changes to passenger vehicle travel demand, electricity generation carbon intensity, and vehicle travel electrification to meet 80% and 90% decarbonization targets for the US light-duty vehicle transport sector. Among these changes, deep decarbonization of electricity generation to near zero is required, unless a severe reduction in vehicle travel occurs. These actions need to be concurrent with achieving a considerably high EV



travel share by 2050. With the current projected travel demand, the EV share of LDV travel cannot be lower than about 67% with a zero-carbon electricity grid to meet an 80% climate target in 2050. Therefore, deep decarbonization of the passenger transport sector during the transition to electrification and automation has a travel budget frontier, and the rates of electricity decarbonization, vehicle travel demand reductions, and travel electrification will determine success.

There are interconnected policy options that can increase the likelihood of a decarbonized passenger transportation sector, but require large scale implementation across several sectors. These policies can be a combination of subsidies to pull technologies to the market, research, development, demonstration, and deployment (RDD&D) to advance technology maturity, regulatory actions, and strategic infrastructure investments. First, rapidly transitioning the power sector to near zero emissions

is the foundation of any transportation decarbonization plan. There are myriad options and pathways to low-carbon electricity, but a national power sector carbon portfolio standard, coupled with carbon pricing, technology subsidies, energy efficiency efforts, and advanced technology RDD&D would speed up the transition.

Similarly for the passenger vehicle fleet, EV subsidies for purchases as well as RDD&D to enable technology breakthroughs in batteries, EV driving ranges, efficiencies, costs, and charging times could increase the market penetration of EVs. But this is unlikely to be sufficient under a time constraint. We show that turnover rate is a barrier to the vehicle fleet transitioning to EVs, due to the long tail of the age distribution of vehicles [56, 65]. The transition of highly utilized public and private fleets enables a higher EV travel share, and helps alleviate a slower fleet penetration rate that is constrained by time and market forces. But the vast majority of the more than 250 million passenger cars and SUVs in the US are owned by individuals, and a rapid transition will require accelerated policies encouraging older gasoline-powered vehicles to exit the fleet. Yet if conventional vehicles were scrapped before the end of their useful lives, there is an asset value for these vehicles and incentives would be needed. For example, a policy inspired by the former Car Allowance Rebate System ('Cash for Clunkers') program, potentially could convince ICEV owners to retire their older vehicles and purchase new EVs [26, 27], but would have a high cost. Over 700 000 relatively more fuel-efficient vehicles were sold under the CARS program [74] which resulted in rebate applications of \$2.88 billion submitted, under the \$3 billion budget provided by Congress to administer the program [75]. If new car sales were restricted to EVs starting in 2021, more than half the fleet would be electrified by 2030. But between 110 and 125 million ICEVs would still be on the road. Using the Cash for Clunkers average tax credit of about \$4200 [76] in 2010 and converting it to 2018 real dollars, the resulting estimated cost of scrapping these ICEVs in 2030 would be approximately \$550–600 billion. In addition, while the potential for existing partially-automated crash avoidance technologies to substantially reduce crashes is very important for safety [68], the average age of the vehicle fleet may continue to increase, further extending the time for existing cars to exit the fleet. EVs could have shorter service lives and/or be driven less as they age relative to similarly-aged ICEVs due to battery degradation. However, electrification could potentially extend the vehicle lifetime since many of the ICEV powertrain parts are no longer needed and primarily a battery replacement would be required to keep an EV in good operating condition. Improvements in the fuel economy of ICEVs as well as lightweight material bodies for all vehicles will help accelerate transport decarbonization, improved vehicle

fuel economy, electrification, and automation could lead to a rebound effect of increased travel due to lower fuel cost and increased convenience [11, 41, 77, 78]. Another potential impact on fuel economy could be the energy required to power the vehicle automation computing and sensing hardware as well as the additional weight [43]. The range of automated EVs could decline under automation and either enhanced battery capacity, increased vehicle efficiency, or an auxiliary energy source will be needed. However, when potential operational effects of connected automated vehicles are included (e.g. eco-driving, platooning, and intersection connectivity), fuel economy and emissions can be improved [43]. Further investigation of the interplay between these effects is a critical area of future work.

We note that we did not consider the life cycle impacts of producing fuels, batteries, vehicles, and infrastructure, which would result in GHG emissions from the industrial sector. Although estimates vary depending on assumptions, the production of an electric vehicle and its battery can generate about 7 to 10 metric tons of CO₂-eq, the production and distribution of gasoline generates an additional 2.66 kg CO₂-eq/gallon, and deploying even very low-carbon electricity infrastructure generates some GHGs [79]. Without both deeply decarbonizing the electricity and industrial sectors in the countries of the supply chains, the CO₂ impacts from producing the millions of EVs required for a large EV fleet would erode some of the climate benefits of an EV transition—requiring the US electrification and miles targets we outlined here to become more stringent. Even if vehicle and battery production GHGs dropped to 3 metric tons, every 10 million EVs sold would generate a GHG pulse of 30 million metric tons before they drove their first mile. This further highlights the need for cross-sectoral deep decarbonization efforts during a transition to EVs.

Finally, to increase the likelihood of achieving deep decarbonization of the passenger vehicle sector, the policies around the future of travel demand deserve more attention. Much of the structural space is determined locally with similar long-term timelines for change—land use and housing policy, walkability and community design, and the historical prioritization of parking. Federal policy can incentivize low-impact outcomes, as well as invest in expanded intercity and intracity electrified transit options, encourage congestion and road pricing, cycling, walking, and other methods to shift and reduce travel demand. Vehicle automation brings another layer of new challenges and opportunities to transportation decarbonization. Prioritizing electric, shared, and low-impact automation that leverages public transit enables the potential for maintaining or enhancing existing passenger mobility while reducing total vehicle miles traveled. Using prices, subsidies, or regulations, to encourage higher levels

of ride sharing and mode shifting to electrified public transit or other alternatives could extend the travel budget under decarbonization, and acts as a hedge in case LDV travel electrification and electric power decarbonization take longer than expected. However, a future where vehicle automation increases total travel and is not primarily electrified creates an environment where deep decarbonization becomes a lot more difficult. Electrification and automation will also change the spatial and temporal aspects of air pollutant emissions from vehicles and power plants, including across urban and rural areas. Continued research and focused policies are needed to ensure equity and environmental justice is improved during a low-carbon transportation transition.

While deep decarbonization of transport remains challenging, we have illustrated that possible pathways exist. A mix of targeted policy interventions to encourage the concomitant objectives of EV adoption, ride sharing and travel demand reduction, low-impact automation, and grid decarbonization increases the likelihood of meeting a deep decarbonization target for US passenger vehicle transport.

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