Supplemental Information For:

Decarbonizing U.S. Passenger Vehicle Transport Under Electrification and Automation Uncertainty Has A Travel Budget

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S1. Units and Metrics

Table S1 below shows the main metrics and units used in the analysis, with comments on the rationale behind the chosen units.

Table S1: Metrics and the associated units used in the analysis.

Metric	Unit	Comment
CO_2 emissions	Million metric tons (Mmt)	Unit used by EIA and TEDB[1,2]
EV adoption	Percentage of EVs in LDV miles or fleet (%EV)	
ICEV Carbon Intensity (CI)	Kilograms of CO_2 per gallon	Used on volume basis to relate to quantity consumed.
Electricity Carbon Intensity (CI)	Grams of CO_2 per kWh	Relates to the output of generated electricity.
ICEV fuel economy (FE)	Miles per gallon (mpg)	Consistent with U.S. regulatory agency reporting.
EV fuel economy (FE)	Miles per kWh	Used to relate to the electric power requirement.
Travel demand	Vehicle miles traveled (VMT)	Consistent with U.S. regulatory agency reporting.

S2. Assumptions

Since CO_2 is about 96% of the direct GHG emissions from the U.S. LDV sector, and to be consistent with EIA reporting, we focused only on CO_2[2,3]. The base case target for the 2050 U.S. LDV CO_2 emissions was calculated using an 80% reduction from 2005 levels. The 2005 level was about 1,133 million metric tons[3]. The 90% reduction target was calculated in similar fashion as shown below,

$$80\%\ 2050\ target = 2005\ level\ \times (1 - 80\%) = 1{,}133 \times 0.2 = 226.6\ million\ metric\ ton$$

$$90\%\ 2050\ target = 2005\ level\ \times (1 - 90\%) = 1{,}133 \times 0.1 = 113.3\ million\ metric\ ton$$

To simplify the analysis and visualization, both the 80% and 90% reduction targeted CO_2 values calculated above were approximated to 250 and 120 million metric tons, respectively. Table S2 shows the historical levels of annual LDV CO_2, obtained by adding the CO_2 emissions from Passenger Cars and Light-Duty Trucks from the Environmental Protection Agency (EPA) 2016 emissions inventory[3].

Table S2: Historical LDV fleet CO_2 emissions[3].

Year	**Passenger Cars (Mmt)**	**Light-Duty Trucks (Mmt)**	**Total LDV (Mmt)**
1990	612.3	312.3	924.6
2005	642.6	490.6	1,133
2012	711.3	281.3	992.6
2013	710.9	281.5	992.4
2014	729.6	304.7	1,034
2015	735.8	297.5	1,033
2016	758.4	306.3	1,065

Table S3 shows the ranges used for the parameters in the results figures as well as the parameters that were kept fixed and/or changed only in sensitivity analysis. The ride sharing effect (i.e. number of passengers per vehicle trip) is represented by the load factor (LF).

Table S3: The values of parameters used in generating the results.

Parameter	Values	Comment
EV share (EV%)	0% - 100%	Varied parameter
ICEV CI (kg/gal)	8.21[4]	fixed
Electricity CI (g/kWh)	0 - 200	Varied parameter
VMT (trillion miles)	2-10	Varied parameter
ICEV FE (mpg)	36.58[2,5]	fixed (varied in sensitivity)
EV FE (miles/kWh)	6	fixed (varied in sensitivity)
Load factor (LF)	1 – 2.5	Varied parameter

The model used in the analysis to estimate the LDV fleet CO_2 emissions level is shown below in equation S1.

$$Total\ LDV\ CO_2(kg) = \frac{\alpha \times (1+\mathrm{L}) \times total\ VMT \times EV\_CI\left(\frac{kg}{kWh}\right)}{EV\_FE\left(\frac{mile}{kWh}\right)} + \frac{(1-\alpha) \times total\ VMT \times ICEV\_CI\left(\frac{kg}{gal}\right)}{ICEV\_FE\ (mpg)} \qquad (\boldsymbol{Eq\ S1})$$

Where α represents the fraction of the LDV miles traveled by EVs, and (1-α) represents the fraction that is traveled by ICEVs. Total VMT represents the total miles traveled by the LDVs in the U.S. for one year. The losses factor (L) used was calculated as (L=0.12+0.0458) to include the charging and grid inefficiencies[6–8].

The fuel economy (FE) term represents the average fuel economy of the corresponding fleet in the given year. The projected fuel economy value for ICEVs are based on the base case projections of technology mix from the VISION Model 2018 which uses the EIA's Annual Energy Outlook (AEO) as shown below in Table S4[2,5]. For ICEVs, we calculated the weighted average fuel economy to be 36.58 mpg based on the projections of each ICEV technology's fleet and actual fuel economy[2,5]. These fuel economy values are expressed in miles per gallon (mpg) and represent the weighted average values 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. That is why we used road degradation factors for each technology from VISION 2018 to better capture real on-road fuel consumption[5].

Table S4: Calculation of the weighted average FE of the ICEV fleet in 2050 based on AEO 2018[2,5].

Vehicle technology	Fleet size (thousands)	Fleet road FE (mpgge)	Fleet share
Auto ICE (gasoline)	114,619	39.88	44%
Auto ethanol	7,151	40.45	3%
Auto diesel	3,556	44.46	1%
Auto hybrid (gasoline)	11,700	60.69	4%
Light truck ICE (gasoline)	95,075	30.28	36%
Light truck ethanol	22,571	29.95	9%
Light truck diesel	8,333	33.01	3%
Light truck hybrid (gasoline)	1,338	46.37	1%
Weighted average FE (mpgee)		36.58	

The EV fleet average FE calculated based on AEO 2018 would be *76.94 mpg or 2.18 mile/kWh*[2,5] as shown in Table S5. This level is considerably low for the EV fleet in 2050 since some current models already surpass that such as the 2018 Tesla Model 3[9]. Even with the on-road conditions adjustment of 30% reduction that VISION 2018 uses, the FE of some current models exceeds the 2.18 miles/kWh derived from AEO 2018 base case. We use a 2050 EV FE base case level of 6 miles/kWh (9.67 km/kWh) 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 (4.8 and 14.5 km/kWh, respectively) as shown in Tables S8-S10.

Table S5: Calculation of the weighted average FE of the EV fleet in 2050 based on AEO 2018[2,5].

Vehicle technology	Fleet size (thousands)	Fleet road FE (mpgge)	Fleet share
auto EV A (100 mile)	1,899	74.24	6%
auto EV B (200 mile)	12,774	80.26	43%
auto EV C (300 mile)	12,688	77.50	42%
Light truck EV A (100 mile)	1,396	60.75	5%
Light truck EV B (200 mile)	738	61.28	2%
Light truck EV C (300 mile)	548	58.05	2%
Weighted average FE (mpgee)		76.94	

The ICEV CI term captures the weighted average combustion carbon intensity of the fuels burned by the ICEVs (i.e. by blended gasoline, diesel, ethanol, and hybrid) vehicles in the fleet. The emission factors for the liquid fuels such as gasoline and diesel were taken from EPA and used to calculate the weighted average CI for ICEVs[4]. Note that we followed the VISION assumption of about 12% ethanol content by volume in the 2050 blended gasoline used by conventional cars and light trucks as shown in Table S6[5].

The EV carbon intensity (CI) here is the direct CO_2 emissions of combustion of fuel for net electricity generation. Unlike the electricity CI, the gasoline CI was kept constant throughout this paper since it is not likely to change as it is related to the fuel combustion chemistry. Table S7 shows a summary of the base case values for 2050.

Table S6: Calculation of the weighted average CI of the ICEV fleet in 2050[2,4,5].

Vehicle technology	Fuel name	Fuel CI (kg CO_2/gal)	Fleet share
Auto ICE (gasoline)	blended gasoline	8.40	44%
Auto ethanol	ethanol	5.75	3%
Auto diesel	diesel	10.21	1%
Auto hybrid (gasoline)	blended gasoline	8.78	4%
Light truck ICE (gasoline)	blended gasoline	8.40	36%
Light truck ethanol	ethanol	5.75	9%
Light truck diesel	diesel	10.21	3%
Light truck hybrid (gasoline)	blended gasoline	8.78	1%
Weighted average CI (kg/gal)		8.21	

Table S7: The base case 2050 projected values for the model input parameters[2,4–8].

Parameter	Values
ICEV CI (kg CO_2/gal)	8.21
Losses factor	16.58%
VMT (trillion miles)	3.3
ICEV FE (mpg)	36.58
EV FE (miles/kWh)	6

To validate our model, we use equation S1 with AEO 2018 reference case values to see if we can reproduce their forecast for the total LDV CO_2 emissions in 2050,

$$\boldsymbol{LDV\ CO_2(kg)} = \frac{\mathbf{10\% \times\ 3302\ \times 10^9\ \times 0.329 \times (1 + 16.58\%)}}{\mathbf{2.18}} + \frac{\mathbf{(100\% - 10\%) \times\ 3302\ \times 10^9\ \times 8.21}}{\mathbf{36.58}}$$

$$= \mathbf{725 \times 10^9}\ \boldsymbol{kg} = \mathbf{725}\ \boldsymbol{Mmt\ CO_2}$$

The EIA projected LDV CO_2 emissions value is around 719[2]. The error percentage between our simplified equation's estimate and EIA's estimate is:

$$\frac{\mathbf{725-719}}{\mathbf{719}}=\mathbf{0.83}\%$$

This shows how the model in equation Eq. S1 can estimate the CO_2 emissions and yield similar results to that projected by EIA AEO 2018[1]. Note that we are not using AEO's assumptions for the EV FE and electricity CI since they are significantly conservative. These LDV emissions are only direct combustion emissions. We take this approach to enable direct comparisons with other projections such as the EIA AEO[1], to map out robust initial parameters that enable policy success, as well as compare with national sectoral-level GHG reporting. The emissions associated with combustion and end use represent most of the carbon emissions in most cases for LDVs[10–14]. The EIA also used only combustion emissions as the Energy-Related Carbon Dioxide Emissions by End Use[2]. Previous static energy analyses have included life cycle emissions[11–18]. Including the life cycle impacts of future nationwide electrification scenarios in 2050 would add additional spatial and temporal uncertainties and is important for future work. The petroleum extraction and refining, gasoline transportation and distribution along with battery production, vehicle manufacturing, and electricity fuels and infrastructure development are the main sources of upstream emissions, which influence the life cycle greenhouse gas emissions from these vehicles[19]. These upstream emissions vary within and across countries and also temporally as demand and technologies change.

S3. Sensitivity analysis

Varying EV Fuel Economy

The 2050 EV fleet average fuel economy (FE) level assumed in Figure 1 is 6 miles/kWh given expected future improvements in battery capacity and lighter weight. However, with the additional energy required for vehicle automation (e.g. computing, sensing, additional weight)[20], the EV fleet average FE could be much lower. Figure S1 shows how the map in Figure 1 would change if the EV fleet average FE is reduced by 50% to 3 miles/kWh, a case of extreme vehicle efficiency degradation. As a result, the feasibility space for a given target level decreases (i.e.

more aggressive electricity decarbonization and travel electrification requirements). For the cases when the electricity CI is reduced to zero, the EV FE becomes irrelevant. However, the results become more sensitive when electricity CI is not closer to zero, when even with 100% miles share, lower electricity CI would be required. For example, for the 90% target, the maximum allowed electricity CI corresponding to 100% EV miles share decreases from 190 to 95 g CO_2/kWh, a reduction of 50%. Therefore, the role of deep decarbonization of electricity becomes more paramount when the vehicle efficiency improvement potential is limited.

To further examine the sensitivity of the results to the EV FE assumption, we considered an upper limit of 9 miles/kWh in addition to the lower limit of 3 miles/kWh discussed above. The effect of changing the EV FE on the requirements for meeting the 80% and targets under three levels of total VMT (2, 3, 4 trillion miles) and electricity CI (0, 50, 100 g CO_2/kWh) is shown in Tables S8-S10. We can see that 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 be reduced to zero CI by 2050.

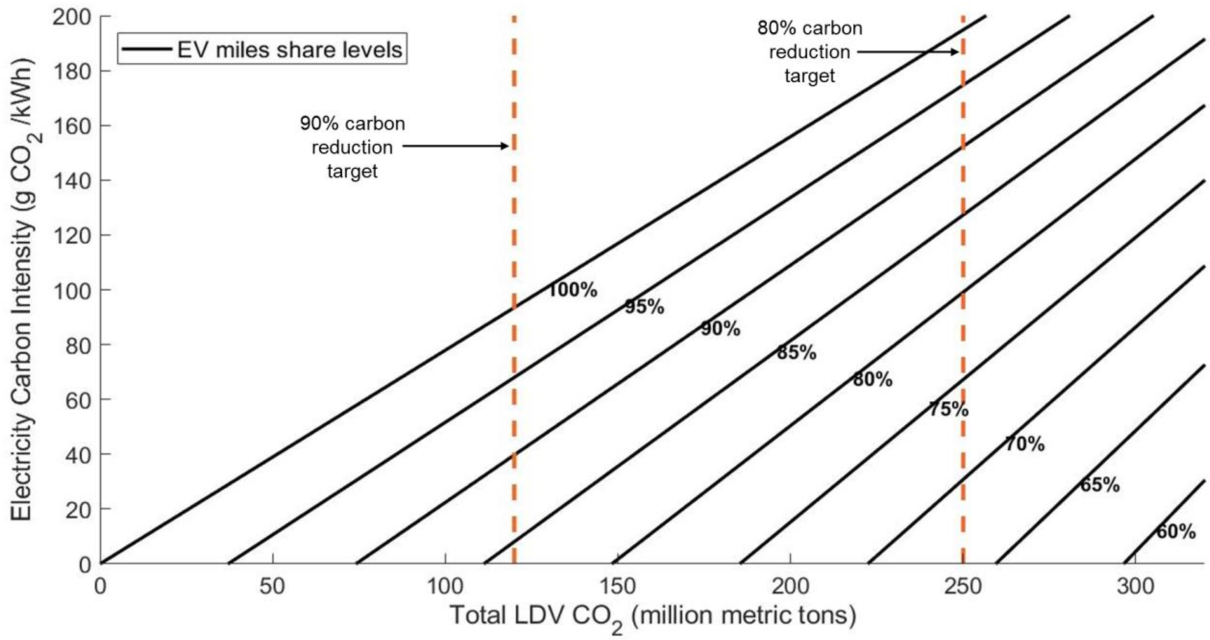

Figure S1: Map of the levels of EV miles share and electricity net generation CI required for a given 2050 total LDV CO2 target. The two vertical dashed lines at 250 and 120 million metric tons represent 80% and 90% reduction in LDV CO2 from 2005 levels, respectively. The EV and ICEV fleets average fuel economy values are 3 miles/kWh and 36.58 mpg, respectively. The triangle formed by the x-axis, a given CO_2 level and the maximum EV miles share represent the feasible space which shrinks with more stringent emissions target. The feasibly space approaches a single point (the point of origin) as the target approaches zero emissions.

Table S8: Sensitivity of 2050 decarbonization requirements to the level of EV FE under a scenario of 2 trillion miles total VMT.

Electricity carbon intensity at 0 g CO_2/kWh and 2 Trillion VMT			
CO_2 reduction target from 2005 in 2050	**EV fuel economy (mile/kWh)**		
	3	**6**	**9**
80% (250 Mmt)	45%	45%	45%
90% (120 Mmt)	73%	73%	73%
Electricity carbon intensity at 50 g CO_2/kWh and 2 Trillion VMT			
CO2 reduction target from 2005 in 2050	**EV fuel economy (mile/kWh)**		
	3	**6**	**9**
80% (250 Mmt)	49%	47%	46%
90% (120 Mmt)	80%	77%	76%
Electricity carbon intensity at 100 g CO_2/kWh and 2 Trillion VMT			
CO_2 reduction target from 2005 in 2050	**EV fuel economy (mile/kWh)**		
	3	**6**	**9**
80% (250 Mmt)	54%	48%	47%
90% (120 Mmt)	89%	80%	78%

Table S9: Sensitivity of 2050 decarbonization requirements to the level of EV FE under a scenario of 3 trillion miles total VMT.

Electricity carbon intensity at 0 g CO_2/kWh and 3 Trillion VMT			
CO_2 reduction target from 2005 in 2050	**EV fuel economy (mile/kWh)**		
	3	**6**	**9**
80% (250 Mmt)	63%	63%	63%
90% (120 Mmt)	82%	82%	82%
Electricity carbon intensity at 50 g CO_2/kWh and 3 Trillion VMT			
CO_2 reduction target from 2005 in 2050	**EV fuel economy (mile/kWh)**		
	3	**6**	**9**
80% (250 Mmt)	69%	66%	65%
90% (120 Mmt)	90%	86%	85%
Electricity carbon intensity at 100 g CO_2/kWh and 3 Trillion VMT			
CO_2 reduction target from 2005 in 2050	**EV fuel economy (mile/kWh)**		
	3	**6**	**9**
80% (250 Mmt)	76%	69%	67%
90% (120 Mmt)	99%	90%	87%

Table S10: Sensitivity of 2050 decarbonization requirements to the level of EV FE under a scenario of 4 trillion miles total VMT.

Electricity carbon intensity at 0 g CO_2/kWh and 4 Trillion VMT			
CO_2 reduction target from 2005 in 2050	EV fuel economy (mile/kWh)		
	3	6	9
80% (250 Mmt)	72%	72%	72%
90% (120 Mmt)	86%	86%	86%
Electricity carbon intensity at 50 g CO_2/kWh and 4 Trillion VMT			
CO_2 reduction target from 2005 in 2050	EV fuel economy (mile/kWh)		
	3	6	9
80% (250 Mmt)	79%	75%	74%
90% (120 Mmt)	95%	90%	89%
Electricity carbon intensity at 100 g CO_2/kWh and 4 Trillion VMT			
CO_2 reduction target from 2005 in 2050	EV fuel economy (mile/kWh)		
	3	6	9
80% (250 Mmt)	87%	79%	76%
90% (120 Mmt)	NA	95%	92%

Effect of a 90% Reduction Target

Figure S2 shows that the more aggressive 90% target results in increasing the required electricity decarbonization and travel electrification compared to the 80% target shown in Figure 2. For example, for a total travel budget of 4 trillion miles, the minimum EV miles share would increase from 72% to 87%, an increase by about one fifth. We note that lower levels of travel such as 1 trillion miles now appear on the Figure which was not the case with the 80% target. Hence, aggressive climate targets would likely require lower total travel budgets for LDVs.

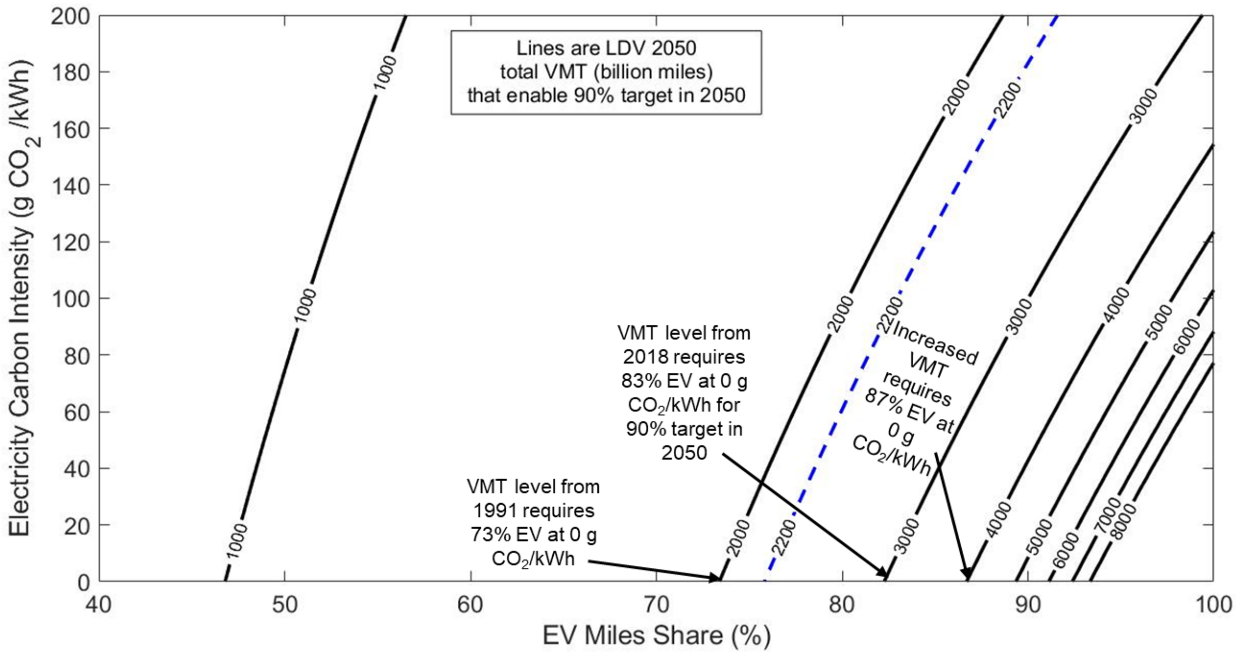

Figure S2: Map of the combinations of the travel demand, electricity generation CI, and EV miles share to meet a 2050 LDV CO_2 target of 120 million metric tons (90% reduction from 2005 level). Meeting the 2050 target with current travel demand requires EV miles share of greater than 82% under a nearly zero-carbon electricity. The impact from the reduced or increased travel due to advanced mobility such as vehicle automation, ridesourcing, and other IT-enabled transport or modal shifts is illustrated. The dashed 2.18 trillion miles line represents reduced total LDV travel through 100% reduction of the urban miles from the states of the 10 most densely populated metropolitan areas. Considering all the states, a 100% shift of urban LDV miles would reduce total LDV travel by around 2.48 trillion miles in 2050.

Improving ICEV Fuel Economy

The effect of improving the average FE of the ICEVs in 2050 from 36.58 mpg to 50 mpg on the combinations of the travel demand, electricity carbon intensity, and mainly on the minimum required EV miles share required to meet the carbon reduction targets of 80% and 90% is shown in Figures S3 and S4, respectively. We can see that for the 80% target, the improved ICEV FE caused the minimum EV miles share for a total VMT of 3 trillion miles to decrease from around 65% (as shown in Figure 2) to about 50% (see Figure S3). The same effect can be observed for the 90% target by comparing Figure S2 to Figure S4. Therefore, improved ICEV FE (50 mpg) can significantly reduce the minimum required EV miles share.

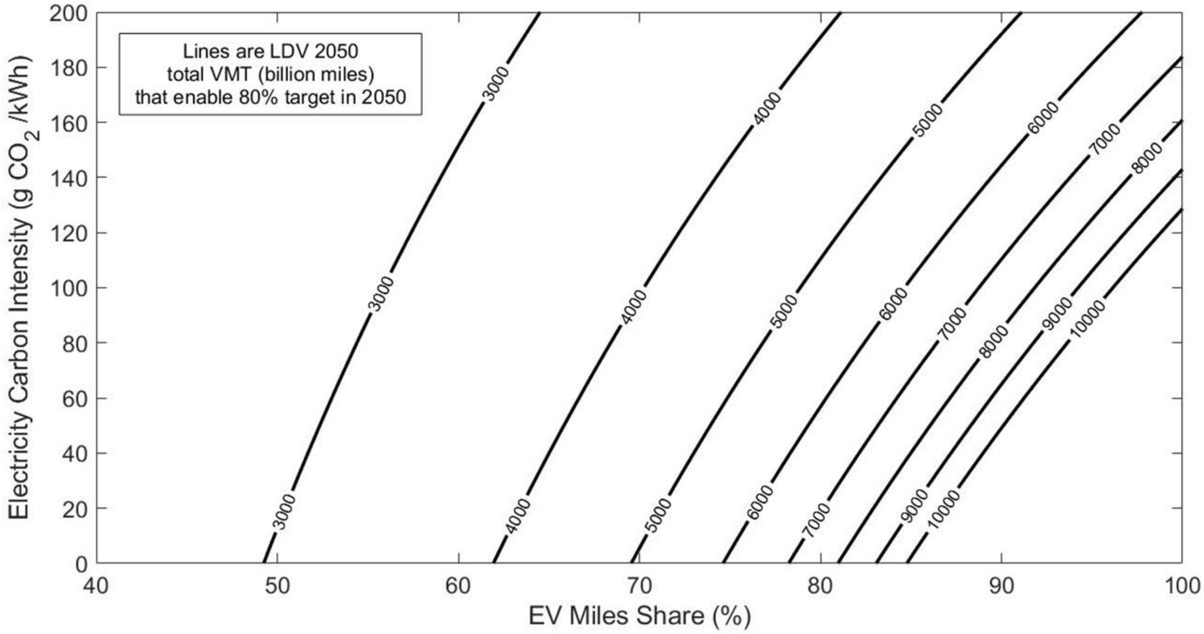

Figure S3: Map of the combinations of the travel demand, electricity generation CI, and EV miles share to meet a 2050 LDV CO_2 target of 250 million metric tons (80% reduction from 2005 level) for an ICEV fleet average fuel economy 50 mpg. Meeting the 2050 target with current travel demand of about 3 trillion miles requires EV miles share of less than 50% under a nearly zero-carbon electricity.

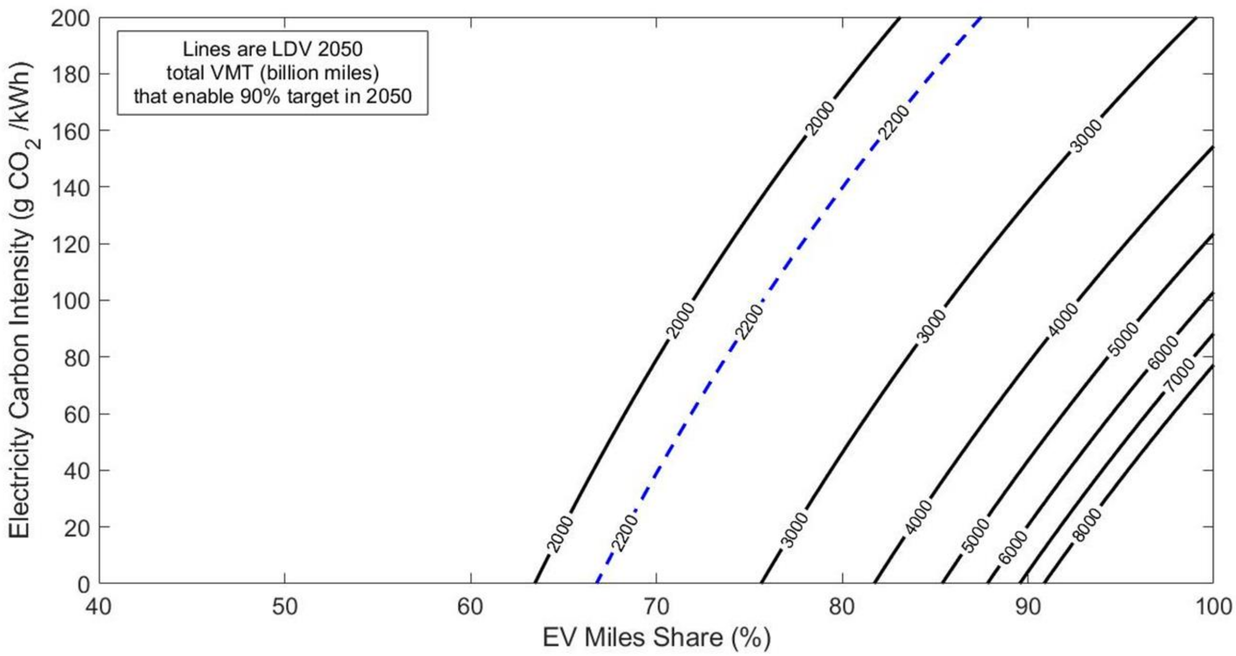

Figure S4: Map of the combinations of the travel demand, electricity generation CI, and EV miles share to meet a 2050 LDV CO_2 target of 120 million metric tons (90% reduction from 2005 level) for an ICEV fleet average fuel economy 50 mpg. Meeting the 2050 target with current travel demand of about 3 trillion miles requires EV miles share of about 75% under a nearly zero-carbon electricity.

Reducing and Shifting Urban VMT

To bound the potential for reducing urban VMT or shifting urban VMT to other modes or advanced mobility, we looked at the top ten U.S. metropolitan areas in terms population-weighted density from the Census Bureau[21]. Population-weighted density is derived as the average of the densities of all the census tracts included within the boundary of each area[21]. These most densely populated areas are shown in Table S11.

Table S11: Top ten U.S. metropolitan areas in terms of weighted population density in 2010 sorted from largest to smallest based on Census Bureau Patterns of Metropolitan and Micropolitan Population Change: 2000 to 2010[21].

Metropolitan statistical area	Population	Land area (mi^2)	Weighted density (persons/mi^2)
New York-Northern New Jersey-Long Island, NY-NJ-PA	18,897,109	6,687	31,251
San Francisco-Oakland-Fremont, CA	4,335,391	2,471	12,145
Los Angeles-Long Beach-Santa Ana, CA	12,828,837	4,848	12,114
Honolulu, HI	953,207	601	11,548
Chicago-Joliet-Naperville, IL-IN-WI	9,461,105	7,197	8,613
San Jose-Sunnyvale-Santa Clara, CA	1,836,911	2,679	8,418
Boston-Cambridge-Quincy, MA-NH	4,552,402	3,487	7,980
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	5,965,343	4,602	7,773
Miami-Fort Lauderdale-Pompano Beach, FL	5,564,635	5,077	7,395
San Diego-Carlsbad-San Marcos, CA	3,095,313	4,207	6,921

We obtained the current VMT data for these metropolitan areas. The Federal Highway Administration (FHWA) Highway Statistics 2018 provides state level VMT data broken down by rural and urban miles[22]. The LDV share of those miles for every state was calculated as the average of their respective shares of Interstate System, Other Arterials, and Other. The resulting estimated urban LDV miles for each of the states that have one or more of the metropolitan areas shown in Table S11 are listed in Table S12. Note that these are estimates of the total urban LDV miles per state and not exactly the VMT of these exact metropolitan areas since higher granularity than state level VMT is not available. Nevertheless, the urban VMT in the states that include the most populated areas provides a useful bounding estimate of the potential travel reduction through modal shifts and increased sharing. To project this level of total urban VMT for the states in Table S12 to 2050, we used the percentage increase from 2018 to 2050 in total LDV VMT from the 2019 Annual Energy Outlook (AEO)[23]. This level is predicted to be a 20% total increase in travel, and assuming the same increase to happen in the urban VMT subcategory, the total urban VMT in 2050 for the states in Table S12 would be around 1,127 billion miles (we round it to 1.1 trillion miles to simplify the illustration).

Table S12: Total 2018 urban LDV VMT[22] sorted from largest to smallest estimates for the states that include one or more of the top ten densely populated metropolitan areas shown in Table S11.

State	Total urban miles (millions)	Share of LDVs (%)	Urban LDV VMT (millions)
CA	290,364	93%	268,644
FL	185,074	93%	171,705
NY	98,207	93%	91,326
IL	82,302	89%	73,575
NJ	72,671	95%	68,996
PA	67,792	91%	61,810
MA	63,703	93%	59,235
IN	51,837	89%	46,310
MD	49,128	93%	45,553
WI	32,528	89%	28,895
HI	9,042	94%	8,538
NH	8,292	94%	7,779
DE	7,710	88%	6,752
Total VMT (trillion)	1,018,648	-	939,118

Using our estimate of the total urban miles in 2050 for the 13 states with the ten most densely populated metropolitan areas, we can assume these areas could implement policies to reduce VMT. We consider 100%, 75%, 50%, and 25% shifting of urban vehicle VMT to public transit and active transport like walking and cycling. The resulting total U.S. LDV VMT in 2050 would then be reduced from 3.3 to 2.18, 2.46, 2.74, and 3.02 trillion miles for modal shift levels of 100%, 75%, 50%, and 25%, respectively. **Figure S5** shows these VMT contour lines (miles budgets) for the 80% climate target and how the feasibility space expands with more modal shift away from LDVs. The upper bound estimate of around 1.1 trillion miles reduction in VMT reduces the minimum travel electrification requirement from 67% to 49% at electricity generation carbon intensity to close to zero to meet a decarbonization target of 80%. Further, we estimated the total 2018 urban LDV miles[22] for all the states to be around 2 trillion miles as shown in **Table S13**. Projecting a 20% increase in 2050 based on the EIA reference case, we get an estimate of up to 2.48 trillion urban miles in 2050 that could be targeted by policy actions to encourage modal shifts, ride sharing, and active transport. This highlights the potential of urban areas to contribute to the decarbonization of the passenger vehicle sector through policy, transport, and land use decisions.

Table S13: Total 2018 total urban LDV VMT[22] for all U.S. states.

State	Total Urban Miles (millions)	Share of LDVs (%)	Urban LDV VMT (millions)
Alabama	42,379	91%	38,438
Alaska	3,211	93%	2,990
Arizona	49,802	86%	42,841
Arkansas	18,888	84%	15,927
California	290,364	93%	268,644
Colorado	38,059	94%	35,919
Connecticut	28,437	90%	25,683
Delaware	7,710	88%	6,752
District of Columbia	3,691	96%	3,550
Florida	185,074	93%	171,705
Georgia	98,607	91%	89,252
Hawaii	9,042	94%	8,538
Idaho	7,529	93%	6,972
Illinois	82,302	89%	73,575
Indiana	51,837	89%	46,310
Iowa	13,566	92%	12,538
Kansas	16,846	90%	15,102
Kentucky	22,928	89%	20,375
Louisiana	30,511	86%	26,295
Maine	4,605	89%	4,083
Maryland	49,128	93%	45,553
Massachusetts	63,703	93%	59,235
Michigan	71,194	92%	65,353
Minnesota	35,766	88%	31,646
Mississippi	16,898	91%	15,421
Missouri	43,429	89%	38,449
Montana	3,945	93%	3,675
Nebraska	9,358	96%	9,022
Nevada	22,618	94%	21,225
New Hampshire	8,292	94%	7,779
New Jersey	72,671	95%	68,996
New Mexico	11,109	90%	10,010
New York	98,207	93%	91,326
North Carolina	79,962	93%	74,010
North Dakota	2,974	91%	2,713
Ohio	79,837	90%	72,223

Oklahoma	23,337	90%	20,954
Oregon	22,259	88%	19,602
Pennsylvania	67,792	91%	61,810
Rhode Island	7,095	93%	6,596
South Carolina	31,205	94%	29,301
South Dakota	2,934	91%	2,682
Tennessee	55,429	88%	48,678
Texas	205,290	91%	187,471
Utah	23,154	81%	18,841
Vermont	2,129	91%	1,948
Virginia	56,327	95%	53,364
Washington	44,940	92%	41,186
West Virginia	9,579	87%	8,361
Wisconsin	32,528	89%	28,895
Wyoming	3,052	86%	2,637
Total	2,261,525	-	2,064,452

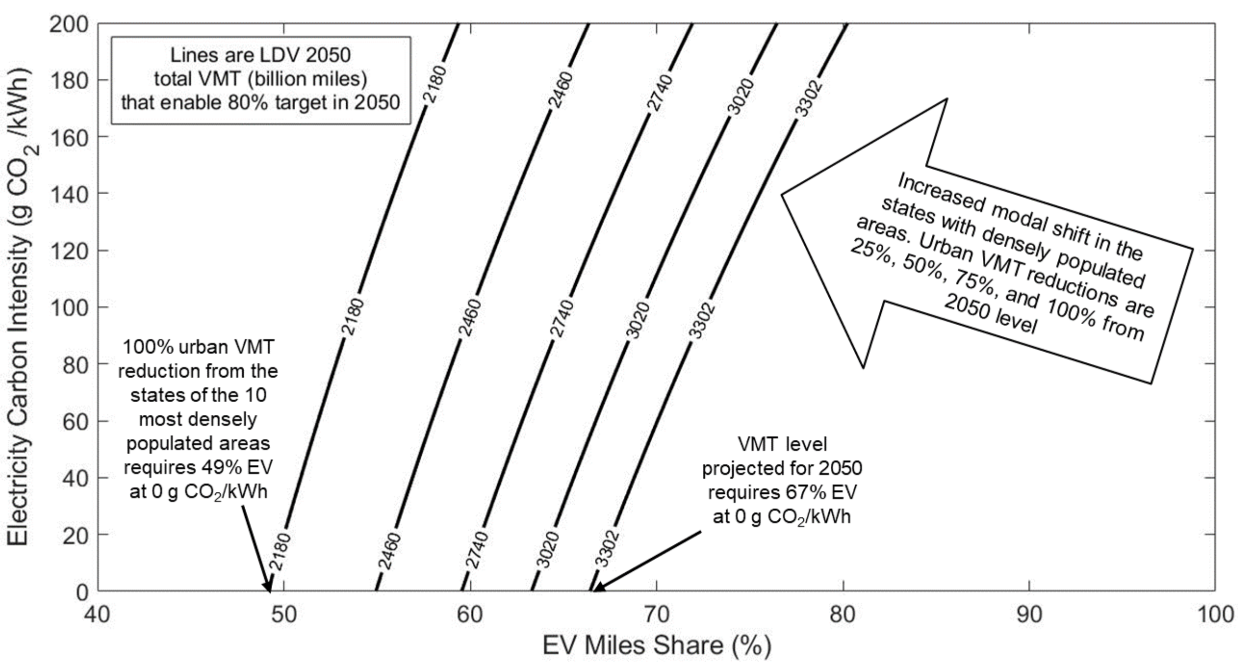

Figure S5: The combinations of the travel demand, electricity generation CO_2 intensity, and EV miles share to meet a 2050 LDV CO_2 target of 250 million metric tons (an 80% reduction from 2005 level). The impact from the reduced travel due to mobility and modal shifts is illustrated. The reduced total VMT levels due to shifting 25%, 50%, 75%, and 100% of the urban miles within the states of the top ten most densely populated metropolitan areas are shown.

Effect of Ride Sharing

The current U.S. LDV Load Factor (LF) was calculated as the vehicle miles weighted average of the car and light truck load factor values from the 2017 National Household Travel Survey (NHTS)[24]. The VMT values for cars and light trucks were taken from the Bureau of Transportation Statistics (BTS)[25]. Table S14 shows the historical VMT and load factor for cars and light trucks as well as the calculated overall load factor for LDVs from 2007 to 2017[1,24,25].

Equation S2 is used to calculate the stock CO_2,

$$LDV\ CO_2(kg) = \frac{PMT}{LF} \times \left[\frac{\alpha \times (1 + L) \times EV\_CI \left(\frac{kg}{kWh}\right)}{EV\_FE \left(\frac{mile}{kWh}\right)} + \frac{(1 - \alpha) \times ICEV\_CI \left(\frac{kg}{gal}\right)}{ICEV\_FE\ (mpg)} \right] \qquad (\boldsymbol{Eq\ S2})$$

Figure S6 and Figure S7 show the effect of ride sharing on the ability of certain combinations of EV miles share and electricity CI to meet either the 80% or 90% target. In all cases, as load factor increases, total VMT declines while PMT demand is met and hence the minimum requirements for miles electrification and electricity decarbonization become lower.

Table S14: Historical U.S. LDV VMT and LF[24,25].

Year	Car VMT (Million miles)	Light Truck VMT (Million miles)	Total LDV miles (Million miles)	Car LF	Light Truck LF	LDV LF
2007	2,104,416	586,618	2,691,034	1.57	1.72	1.60
2008	2,024,757	605,456	2,630,213	1.55	1.84	1.62
2009	2,015,714	617,534	2,633,248	1.55	1.84	1.62
2010	2,025,745	622,712	2,648,456	1.55	1.84	1.62
2011	2,046,282	604,175	2,650,458	1.55	1.84	1.62
2012	2,062,828	601,232	2,664,060	1.55	1.84	1.62
2013	2,074,423	603,307	2,677,730	1.55	1.84	1.62
2014	2,072,071	638,484	2,710,556	1.55	1.84	1.62
2015	2,147,840	631,852	2,779,693	1.55	1.84	1.62
2016	2,191,764	657,954	2,849,718	1.54	1.82	1.60
2017	2,220,801	656,578	2,877,378	1.54	1.82	1.60

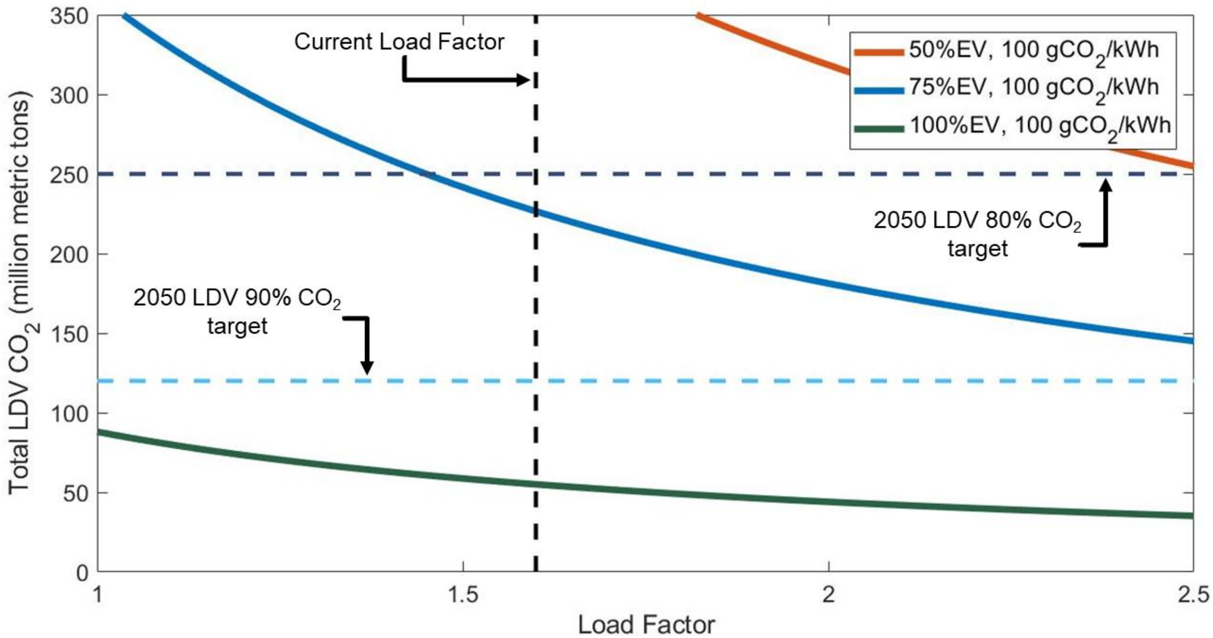

Figure S6: The 2050 U.S. LDV total CO_2 emissions as a function of the load factor for different levels of travel electrification and electricity generation carbon intensity (50% EV- 100 g CO_2/kWh, 75% EV- 100 g CO_2/kWh, 100% EV- 100 g CO_2/kWh). The vertical line crossing the EIA 2050 projected conditions indicates the current load factor of 1.6. The two horizontal dashed lines indicate the 80% and 90% midcentury decarbonization targets.

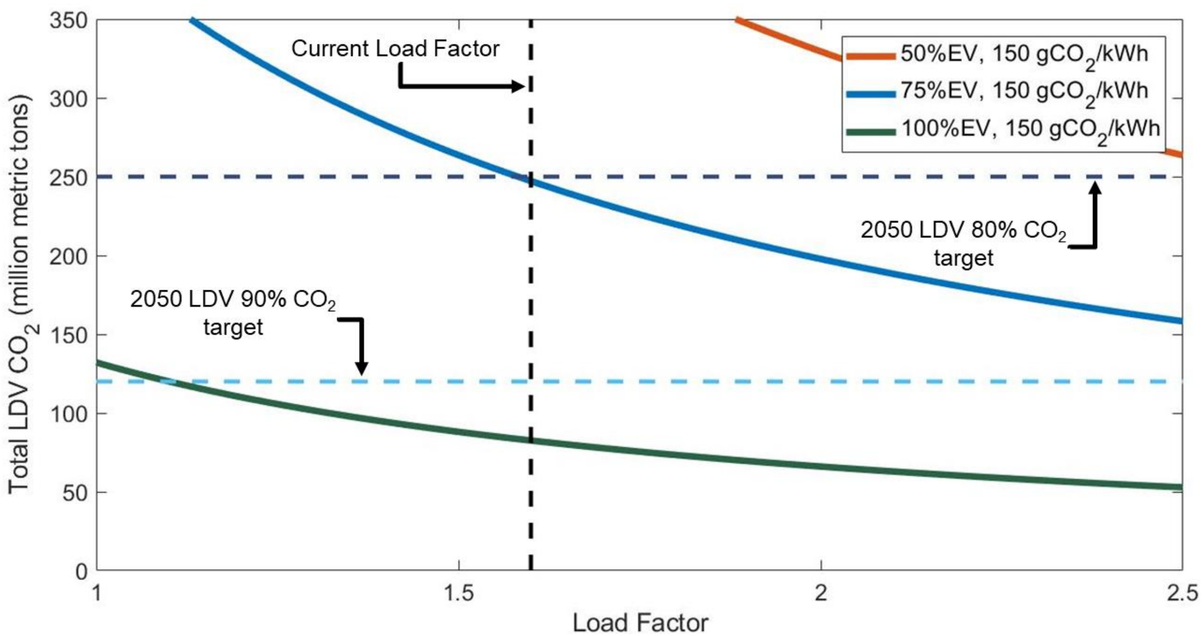

Figure S7: The 2050 U.S. LDV total CO_2 emissions as a function of the load factor for different levels of travel electrification and electricity generation carbon intensity (50% EV- 150 g CO_2/kWh, 75% EV- 150 g CO_2/kWh, 100% EV- 150 g CO_2/kWh). The vertical line crossing the EIA 2050 projected conditions indicates the current load factor of 1.6. The two horizontal dashed lines indicate the 80% and 90% midcentury decarbonization targets.

Varying EV Utilization

Considering that new vehicles are on average driven more than older ones, it means that the targeted travel share can be reached earlier than the physical stock share of vehicles. We used typical annual miles by age distributions[5] for passenger cars and light trucks shown in Table S15 to calculate the difference between the miles share and stock share.

Table S15: Typical annual miles traveled by age for U.S. passenger cars and light trucks[5].

Vehicle age	Typical annual miles	
(years)	Passenger cars	Light trucks
0	13,852	15,300
1	13,440	14,798
2	13,041	14,311
3	12,656	13,840
4	12,284	13,384
5	11,927	12,944
6	11,582	12,519
7	11,251	12,110
8	10,934	11,716
9	10,631	11,338
10	10,341	10,975
11	10,065	10,627
12	9,802	10,295
13	9,553	9,979
14	9,317	9,678
15	9,096	9,392
16	8,887	9,122
17	8,693	8,868
18	8,511	8,628
19	8,344	8,405
20	8,190	8,197
21	8,050	8,004
22	7,923	7,827

23	7,810	7,665
24+	7,711	7,519

As shown in Figure S8 for the case of about 80% EV fleet share by 2050, the miles share always exceed the stock share and the annual difference can get up to 7%, depending on the number of years since starting to sell only EVs. The other cases from Figure 4 in the main text show the same pattern. The difference is at its maximum when the remaining ICE fleet still makes a considerable portion of the overall stock is relatively old, so it is driven much less. 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.

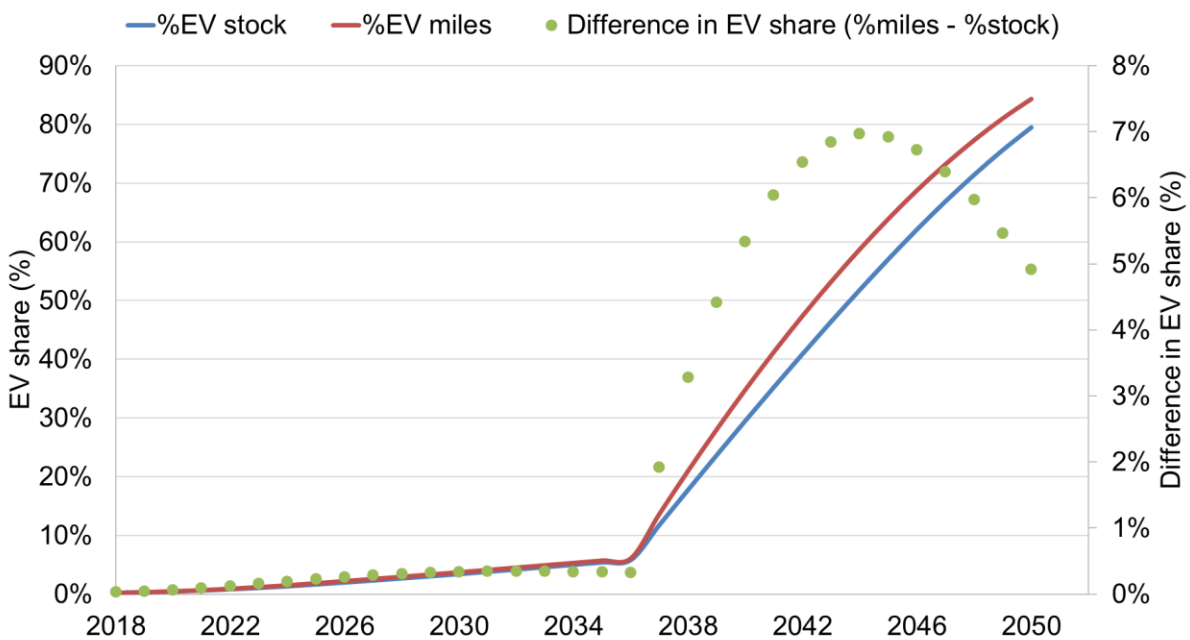

Figure S8: The EV stock share, miles share, and the difference between them for the case of 80% EV stock share by 2050 shown in Figure 4.

EIA projects an EV miles share in 2050 as 10% and projects a 2050 EV fleet share of 9.94%[2]. As shown above, vehicles that travel more than the average annual miles per vehicle should be the primary target for electrification. For EVs to travel 75% of the total 3.3 trillion LDV miles projected for 2050, the primary pathway is through a 75% EV fleet share, and each EVs would need to drive on average an annual VMT of about 11,600 miles. Yet for the EVs to drive the same 75% of miles share with a lower fleet share such as 50%, they would need to drive more miles relative to conventional cars and travel about 17,400 miles per year. A more extreme case is if 75% of the miles are to be traveled by EVs that are only 10% of the fleet. In this case, the EVs will need to travel (on average) about 87,200 miles annually which is greater than what a typical New York City taxi travels in a year[26]. Figure S9 shows the impact of decoupling the EV miles 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. It was generated by assuming total VMT of 3.3 trillion miles and a total fleet size of 284 million LDVs as projected by the EIA AEO 2018[2]. Then, for each level of EV stock share considered (25%, 50%, 75%, 100%), the EV mile share was varied from 1% to 100% and used into Equation S3 to obtain the annual VMT per EV,

$$Annual\ VMT\ per\ EV = \frac{percentage\ EV_{miles} \times total\ VMT}{percentage\ EV_{fleet} \times total\ fleet} \quad (\boldsymbol{Eq\ S3})$$

Another challenge is whether these highly utilized EVs with low fleet share can serve the passenger demand. Highly utilized EVs require significant increases in the number of rides that are shared from current levels. In 2014, New York City taxis made about 485,000 trips per day, moving about 600,000 passengers per day[26]. This results in a ratio of about 1.2 passengers per trip, indicating that most taxi trips were made to deliver single passengers.

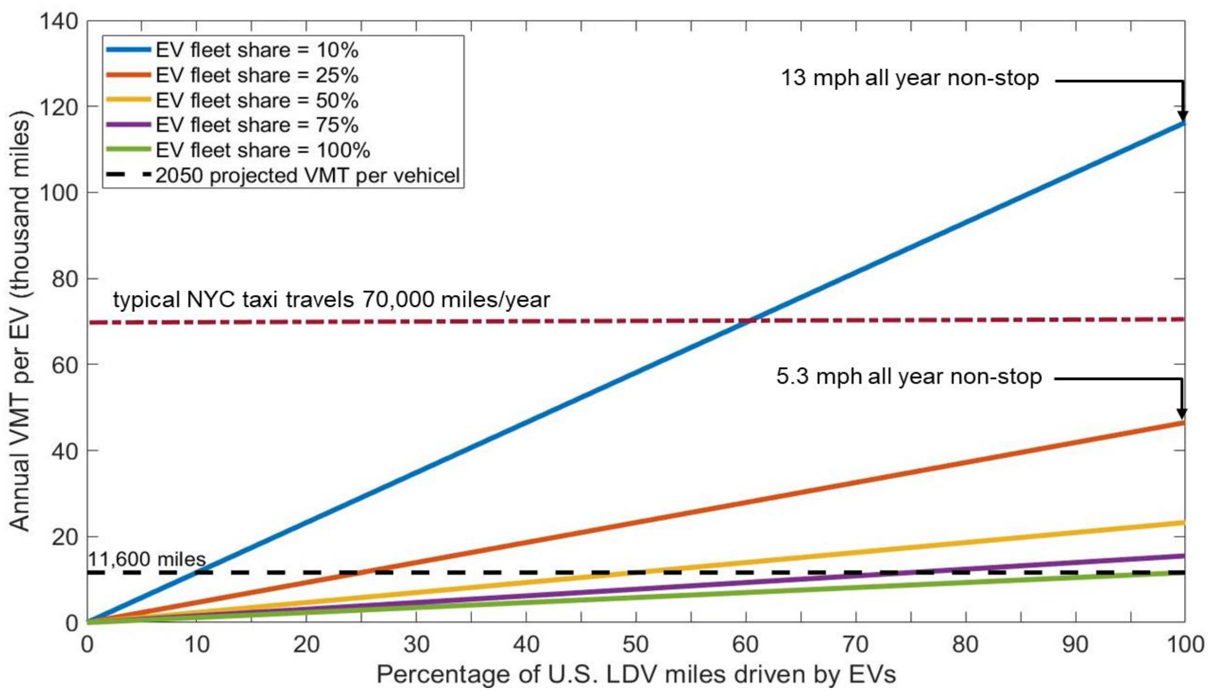

Figure S9: Vehicle utilization impact on EV stock share showing how a certain EV miles share target (x-axis) can be met with different levels of physical stock share through changing the average annual utilization of the EVs from the annual average, with typical New York City (NYC) taxi travel shown[2,26].

Vehicle Stock Model

Our fleet stock model utilizes survival rates for cars and light trucks from the Oak Ridge National Laboratory, Transportation Energy Data Book, Table 3.12[1]. The curves assume a maximum possible life of 31 years for any LDV. These survival curves were applied to the EVs fleet under the assumption that EVs will have the same survival behavior as conventional vehicles. However, EVs are likely to have different survival rates given their enhanced reliability and fewer parts, and automation features are likely to extend the survival curves for all vehicles. Table S16 shows the survival rates used in modeling the LDV fleet[1].

The stock model uses the AEO 2018 projections[2] for LDV sales and the corresponding shares of EVs and ICEVs. The 2018 surviving vehicles by age distribution for EV and ICEV cars and light trucks was taken from the 2018 distribution in VISION 2018 model[5], shown in Table S17 and Table S18. For EVs, the 2018 surviving vehicles by age distribution for the “EV A” technology was assumed to be representative for EVs since it is the major one. These distributions were used to find how many vehicles fall under each age for the vehicles of one year of age or older. The number of vehicles with age of zero (i.e. newly sold vehicles) for each technology as taken from the AEO 2018[2]. Then, the survival curves are applied to each fleet to update the age distribution for the next year by adding the new model vehicle sales for each year as age zero and discounting each year’s vehicles. Every year, the age zero vehicles are the new sales ones as projected by AEO. Since the fleet by age distribution form VISION terminates after age 23 and combines all the remaining vehicles in one age category that is “24+”, we assumed all the remaining ICEVs to be 24 years old. This provides a conservative worst-case assumption of the required EV penetration since the remaining ICEVs could be older and retire faster. However, such an assumption is not expected to affect the outcomes since the remaining vehicles in the “24+” age category account for only less than 1% of the vehicles[5].

The sum of the vehicles across ages for a given technology in a given year yields its total stock, then the share of that technology in the total LDV stock can be calculated. For the cases when all the LDV sales become EVs in a given year, all the projected passenger car sales become EV car sales and the same applies for EV light trucks. The sales of ICEVs in these years become zero and the remaining ICEV car and light truck stocks get retired through applying the survival curves to the fleet age distribution.

Table S16: Survival rates for cars and light trucks by vehicle age[1].

Vehicle age	Estimated survival rate	
(years)	Passenger cars	Light trucks
0	1.000	1.000
1	0.997	0.991
2	0.994	0.982
3	0.991	0.973
4	0.984	0.960
5	0.974	0.941
6	0.961	0.919
7	0.942	0.891
8	0.920	0.859
9	0.893	0.823
10	0.862	0.784
11	0.826	0.741
12	0.788	0.697
13	0.718	0.651
14	0.613	0.605
15	0.51	0.553
16	0.415	0.502
17	0.332	0.453
18	0.261	0.407
19	0.203	0.364
20	0.157	0.324
21	0.120	0.288
22	0.092	0.255
23	0.070	0.225
24	0.053	0.198
25	0.040	0.174
26	0.030	0.153
27	0.023	0.133
28	0.013	0.117

29	0.010	0.102
30	0.007	0.089
31	0.002	0.027

Table S17: Distribution of the 2018 EV cars and light trucks fleet by age from VISION 2018 model[5].

Vehicle age	Share of the technology stock	
(years)	Passenger cars	Light trucks
1	16%	40%
2	18%	40%
3	14%	1%
4	25%	8%
5	15%	0%
6	6%	0%
7	5%	0%
8	0%	3%
9	0%	2%
10	0%	1%
11	0%	0%
12	0%	0%
13	0%	0%
14	0%	0%
15	0%	0%
16	0%	1%
17	0%	1%
18	0%	1%
19	0%	1%
20	0%	0%
21	0%	0%
22	0%	0%
23	0%	0%
24+	0%	0%

Table S18: Distribution of the 2018 ICEV cars and light trucks fleet by age from VISION 2018 model[5].

Vehicle age	**Share of the technology stock**	
(years)	**Passenger cars**	**Light trucks**
1	8%	7%
2	8%	8%
3	7%	10%
4	7%	7%
5	6%	6%
6	6%	5%
7	5%	4%
8	4%	4%
9	4%	4%
10	4%	4%
11	5%	5%
12	5%	5%
13	3%	5%
14	4%	4%
15	4%	4%
16	3%	3%
17	3%	3%
18	3%	2%
19	3%	2%
20	2%	2%
21	2%	1%
22	2%	1%
23	1%	1%
24+	1%	1%

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