Transportation Sector GHG Reduction Pathway Analysis Project

Paulina Nelson, Jenn Kane, David Baker

Introduction

We decided to focus our analysis on greenhouse gas (GHG) emissions from commuting in the United States. Commuting accounts for about 16% of all trips made by individuals, 28% of miles traveled by private vehicles, and 39% of passenger miles on public transit [1]. In our analysis, we first estimate current emissions, then we project an estimate for 2050 based on business-as-usual, accounting for current, moderate, trends in electrification of personal vehicles and grid renewables. Then we imagine a scenario of advanced GHG reduction guided by technology and policy adoption. The policies we look at incentivize behavior change to a higher mix of cleaner mode choices. The technology we adopt is autonomous vehicles with significant ridesharing to improve drive cycle efficiency and increase electrification of automobiles. We focus our analysis only on emissions incurred during vehicle operation; we are not using a full lifecycle analysis.

Scenario 1: Business-as-usual

$$GGE_{total} = \sum_{mode} GGE_{mode} = \sum_{mode} (\frac{GGE}{E})(\frac{E}{PKT})(PKT)$$

Equation 1. GGE is greenhouse gas emissions, E is energy, PKT is passenger kilometers travelled.

Our analysis began by calculating an estimate for the *current* level of GHG emissions due to commuting. Our methodology is guided by Equation 1. We'll now discuss how we cobbled together data for each term in the equation.

Passenger Kilometers Travelled

The Bureau of Transportation Statistics provides data on the principal means of transportation to work from 2022, so our analysis begins with that dataset (**Commuters** column in Table 1) [4]. We must note that this dataset refers to the mode of travel used to commute *most frequently*. If a surveyee's commute involved multiple modes of transportation, they were asked to specify the one used for the longest portion during the trip.

This dataset breaks commuters into these categories: automobile: drives self, automobile: carpool broken down by carpool size, public transportation, taxicab, bicycle, motorcycle, walks only, other means, and works from home. We had to ignore the *other means* category as we had no good way to associate an emissions factor with this category. We further broke down the public transportation pool into bus, light rail, subway, commuter rail, and ferry boat. The Transportation Energy Databook (TED) provides one-way commute distances for each of these modes from 2017 data, (**Commute Distance** in Table 1) [2, 3]. We assume that there are 250 working days in a year, given a 5-day work week and 2 weeks of vacation. Now we have all the pieces we need to get passenger kilometers traveled over a year, by mode:

$$PKT = (2 \times distance_{one-way})(250\frac{\text{trips}}{\text{year}})(number\ of\ commuters)$$

Equation 2. PKT per year for each mode.

Energy Intensity

Next, for each mode we needed an energy intensity which required us to break out the mode by fuel for some modes including automobiles and buses.

We decided to lump together diesel and gasoline automobiles (and taxicabs) into an internal combustion (IC) group, and we also had an electric (EV) “fuel”. We decided to not break EV out further by type of EV (battery, plugin-hybrid, etc.) because we had no data for how they are divided for commuting. The current breakdown of light duty vehicles by fuel type is 98.84% IC, 1.16% EV, and, for lack of more specific data, we assumed the same breakdown for taxicabs [Table A1]. The energy intensity of IC automobiles and motorcycles were found in BTS data [8].

We also split buses into IC and EV groups, with 97.5% of buses currently being diesel IC the other 2.5% electric [5]. We assumed buses had an average vehicle occupancy of 10.7 passengers [6]. For electric buses, we found a figure of 2.36 kWh per vehicle mile traveled [7]. For IC buses, we used a figure of 5.3 mpg_{diesel}, which we can then convert to energy intensity using the energy density of diesel, 138,000 btu/gallon, as in Equation 3 [7].

$$\frac{E}{PKT} = \frac{\text{gallon}_{\text{diesel}}}{\text{5.3 miles}} \cdot 138000 \frac{\text{BTU}}{\text{gallon}_{\text{diesel}}} \cdot \frac{\text{vehicle}}{\text{10.7 passengers}} \cdot \frac{\text{mile}}{\text{1.6 km}} \cdot \frac{\text{0.000293071 kWh}}{\text{BTU}} = 0.448 \ \frac{\text{kWh}}{\text{PKT}}$$

Equation 3. Energy intensity calculation for diesel buses. This methodology is used to calculate all other modes' energy intensities.

Energy intensities for other forms of public transportation were found in section 7 of TED. We considered bicycling, walking, and working from home to have emissions factors of zero.

Fuel Emissions Intensity

Carbon intensity of transportation modes depends on the carbon intensity of the fuel.

$$\frac{kg_{CO_2}}{kWh} = \frac{kg_{CO_2}}{kg_{fuel}} * \rho_{fuel}/U_{fuel} = \frac{8 * 44.011}{114.23} * \frac{0.755}{\frac{9.5076}{1000}} = 243.32 \frac{kg_{CO_2}}{kWh}$$

Equation 4. Carbon intensity of fuels calculation. We are not showing this work for each fuel, but this is exemplary of how we calculated the diesel carbon intensity as well.

For IC vehicles using gasoline fuel $\frac{kg_{CO_2}}{kg_{fuel}}$ is found stoichiometrically assuming an average gasoline chemical formula of C_8H_{18} and the carbon intensity is found by multiplying by fuel density and fuel energy density. The same equation can be applied to diesel with an average chemical formula of $C_{12}H_{23}$ which gives a carbon intensity of $250.32\frac{kg_{CO_2}}{kWh}$ [26]. This calculation being so similar is why we chose to combine gasoline and diesel vehicles into the IC vehicle category. For electric vehicles the carbon intensity of the mode depends on the carbon intensity of the electric grid, which we found to be $390\frac{kg_{CO_2}}{kWh}$ from an analysis of the United States energy grid by the EIA [11].

2050 Projection

Even with business-as-usual, some variables are constant and others change by 2050. Based on commute mode trends over the last 20 years, there was an increase in working from home between 2019 and 2020, partly because of COVID, but it has leveled out [9]. We therefore assumed the percentages of each mode remain the same in 2050 as today, though the number of commuters increases slightly since the expected US population in 2050 is 17% higher than today [10]. With our current data, we calculated that 48% of the population is included as a commuter, and we maintained this percentage in 2050.

We project the proportion of EV automobiles on the road in 2050 to be 25%, a conservative estimate in an NREL EV charging station study [13]. We could not find a good projection of EV bus share, but it would be reasonable to assume a similar 25% share. The shift to more EVs is accompanied by a reduction in the grid's emissions intensity. The most conservative scenario presented in the NREL Renewable Electricity Futures study predicts a 10% reduction in grid emissions by 2050, so we use that number [12].

Increasingly stringent EPA fuel economy standards also drive improvements in IC engine efficiency. Technologies like gasoline direct injection, turbo, continuous variable transmission, and more will drive these engine improvements, but some efficiency improvements are effectively thwarted by shifts away from cars and towards SUVs [14]. In our projection, we use a conservative 20% improvement in energy intensity of IC engines, although we did find numbers over 50% in the literature [15]. We apply this 20% improvement to all IC engines, regardless of mode.

Table 1. GHG emissions estimate for commuter transportation in 2024. Total is 253.71 million tonnes per year.

Commute Mode	Percentage	Commuters (thousands)	1-way Commute Distance (km)	Mode Energy Intensity (kWh/PKT)	PKT	Emissions for 1 kWh Fuel (kg/kWh)	Annual Emissions (kg/year)	Annual Emissions (million tonnes/year)
Automobile (total)	77.30%	124,126	19.54					
Drives self	68.66%	110,245						
Carpool, total	8.64%	13,881						
2-person	6.38%	10,240						
3-person	1.35%	2,174						
4+ person	0.91%	1,467						
Automobile (IC)	76.40%	122,686	19.54	0.876				
Drives self	67.86%	108,966	19.54	0.876	1,064,381,431,344	0.247	230,064,306,358.07	230.06
Carpool, total	8.54%	13,720						
2-person	6.30%	10,121	19.54	0.438	98,864,037,888	0.247	10,684,650,084.39	10.68
3-person	1.34%	2,149	19.54	0.292	20,989,298,669	0.247	1,512,267,531.48	1.51
4+ person	0.90%	1,450	19.54	0.219	14,163,431,990	0.247	765,350,667.67	0.77
Automobile (EV)	0.90%	1,440	19.54	0.184				
Drives self	0.80%	1,279	19.54	0.184	12,491,728,656	0.446	1,024,646,534.74	1.02
Carpool, total	0.10%	161						
2-person	0.07%	119	19.54	0.092	1,160,282,112	0.446	47,586,650.26	0.05
3-person	0.02%	25	19.54	0.061	246,333,331	0.446	6,735,245.94	0.01
4+ person	0.01%	17	19.54	0.046	166,224,010	0.446	3,408,672.65	0.00
Public transportation (total)	3.12%	5,013						
Bus (total) (Motor bus, Commuter, Trolley Bus)	1.25%	2,002	16.56					
Bus (IC)	1.22%	4,888	16.56	0.448	40,469,949,000	0.250	4,538,348,941.43	4.54
Bus (EV)	0.03%	50	16.56	0.221	414,501,975	0.446	40,811,167.17	0.04
Light rail / Street Car	0.18%	288	15.84	0.239	2,283,725,664	0.446	244,059,978.95	0.24
Heavy rail / Subway	0.88%	1,410	15.84	0.143	11,164,881,024	0.446	711,162,104.78	0.71
Commuter rail / Railroad	0.59%	945	40.91	0.291	19,333,877,938	0.250	1,408,611,673.86	1.41
Ferry boat	0.04%	64	18.62	10.822	596,690,611	0.23	1,499,503,320.81	1.50
Taxicab (+DR) (total)	1.16%	1,870	9.46					
Taxicab (+DR) (IC)	1.15%	1,848	9.46	0.438	8,738,800,224	0.247	944,241,151.22	0.94
Taxicab (+DR) (EV)	0.01%	22	9.46	0.092	102,559,776	0.446	4,206,284.09	0.00
Motorcycle	0.10%	217	16.19	0.501	1,756,832,000	0.243	214,184,834.19	0.21
Bicycle	0.50%	731	4.35	-	1,590,656,000	-	-	-
Walks only	2.40%	3,855	1.90	-	3,669,960,000	-	-	-
Works at home	15.20%	24,382	-	-	-	-	-	-
Total	99.8%	160194			1,302,585,202,212		253,714,081,202	**253.71**

Table 2. (below) GHG emissions estimate for commuter transportation in 2050, assuming business-as-usual. Total is 202.71 million tonnes per year, which is a 20% reduction from 2024.

Commute Mode	Percentage	Commuters (thousands)	1-way Commute Distance (km)	Mode Energy Intensity (kWh/PKT)	PKT	Emissions for 1 kWh Fuel (kg/kWh)	Annual Emissions (kg/year)	Annual Emissions (million tonnes/year)
Automobile (total)	77.30%	144,297	19.54					
Drives self	68.66%	128,161						
Carpool, total	8.64%	16,137						
2-person	6.38%	11,904						
3-person	1.35%	2,527						
4+ person	0.91%	1,705						
Automobile (IC)	57.98%	108,223	19.54	0.701				
Drives self	51.49%	96,121	19.54	0.701	938,905,186,047	0.247	162,340,455,221.10	162.34
Carpool, total	6.48%	12,103						
2-person	4.78%	8,928	19.54	0.350	87,209,298,427	0.247	7,539,417,939.43	7.54
3-person	1.02%	1,895	19.54	0.234	18,514,942,850	0.247	1,067,102,513.04	1.07
4+ person	0.69%	1,279	19.54	0.175	12,493,753,984	0.247	540,054,986.19	0.54
Automobile (EV)	19.33%	36,074	19.54	0.184				
Drives self	17.16%	32,040	19.54	0.184	312,968,395,349	0.402	23,104,391,037.20	23.10
Carpool, total	2.16%	4,034						
2-person	1.59%	2,976	19.54	0.092	29,069,766,142	0.402	1,073,014,486.92	1.07
3-person	0.34%	632	19.54	0.061	6,171,647,617	0.402	151,870,670.22	0.15
4+ person	0.23%	426	19.54	0.046	4,164,584,661	0.402	76,860,949.82	0.08
Public transportation (total)	3.12%	5,828						
Bus (total) (Motor bus, Commuter, Trolley Bus)	1.25%	2,333	16.56					
Bus (IC)	0.94%	1,750	16.56	0.358	14,490,414,000	0.250	1,299,978,016.53	1.30
Bus (EV)	0.31%	583	16.56	0.221	4,830,138,000	0.402	428,010,535.81	0.43
Light rail / Street Car	0.18%	336	15.84	0.239	2,661,196,032	0.402	255,959,948.26	0.26
Heavy rail / Subway	0.88%	1,643	15.84	0.143	13,010,291,712	0.402	745,837,217.26	0.75
Commuter rail / Railroad	0.59%	1,101	40.91	0.233	22,529,518,349	0.250	1,313,149,598.02	1.31
Ferry boat	0.04%	75	18.62	10.822	695,315,866	0.23	1,746,008,306.73	1.75
Taxicab (+DR) (total)	1.16%	2,174	9.46					
Taxicab (+DR) (IC)	1.15%	2,149	9.46	0.350	10,158,924,505	0.247	878,150,256.20	0.88
Taxicab (+DR) (EV)	0.01%	25	9.46	0.092	119,226,552	0.402	4,400,854.73	0.00
Motorcycle	0.10%	186.672	16.19	0.401	1,511,296,512	0.243	147,400,226.24	0.15
Bicycle	0.50%	933.36	4.35	-	2,030,991,360	-	-	-
Walks only	2.40%	4,480	1.90	-	4,265,081,856	-	-	-
Works at home	15.20%	28,374	-	-	-	-	-	-
Total	99.8%	186,273			1,485,799,969,820		202,712,062,764	**202.71**

Scenario 2: Advanced GHG Reduction

Policy Pathway

Over 90% US of emissions are generated from single-passenger automobiles in our baseline case. Mode shares are assumed to be constant between now and 2050 without policy intervention due to skewed funding for highways relative to public transit [16], limited accessibility of public transit to labor markets, and urban design that historically favors automobiles. We propose policy initiatives that improve public transit such that commute modes shifts from individual vehicles as illustrated in Figure 1.

We assumed the implementation of federal policies that increase the probability of transit ridership using existing bus transit capacity. Wait times can be reduced by increasing the number of buses and stop frequency along existing routes. Reducing both travel and wait time is possible by assigning buses dedicated lanes and give them priority at traffic lights to decrease travel time relative to cars, as implemented in Bogotá Columbia [17]. By comparing results from the Logit model business-as-usual scenario with reduced wait and travel time for bus transit by 2 minutes each, we find a 10% probability increase of a commuter choosing the bus over an automobile. We applied this mode shift to 50% of commuters based on estimates that roughly half of Americans live within 0.75 miles of an existing bus route, and over half of workplaces are within 0.25 miles of a bus line [18]. With increased ridership, we also increased the passenger capacity of buses from 10.7 to 20.

We considered two incentive programs, one implemented by employers with the support of the federal government, and the second an increase in the federal gasoline tax. Commute Trip Reduction Programs (CTR) give commuters resources and incentives to reduce their automobile trips, typically including financial incentives for transit, walking, and cycling. We assumed that if

50% of companies implemented CTRs with financial incentives, each would achieve 30% reduction in automobile trips [19]. Increasing the federal gasoline tax would also make driving alone more expensive and incentivize alternative methods of commuting. We assumed an increase of 5 cents/gallon where each percent increase in gas price correlates to 0.14% increase in carpooling and transit ridership, split evenly between bus and rail, and directly reduces IC engine commutes [20].

We also assumed federal policy requires thoughtful urban planning to create more compact, walkable, and bikeable communities with increased access to transit, as seen in the Bay Area [21]. One study estimates that 8-13 years of transit-oriented development results in 12% decrease in the share of residents who drive alone to work [22]. Our model reduces automobile travel by 12%, shifting that to biking, walking, and transit equally.

Following a local sensitivity analysis, we found that the two most influential policy variables on final emissions are the travel time assumed for bus trips compared to automobiles and the adoption of transit-oriented community development across the nation. The most effective policy measure for emission reduction is displacing individual vehicle miles traveled with walking and biking, which contribute little to no emissions, or increasing the probability of choosing transit with a higher load factor, like buses.

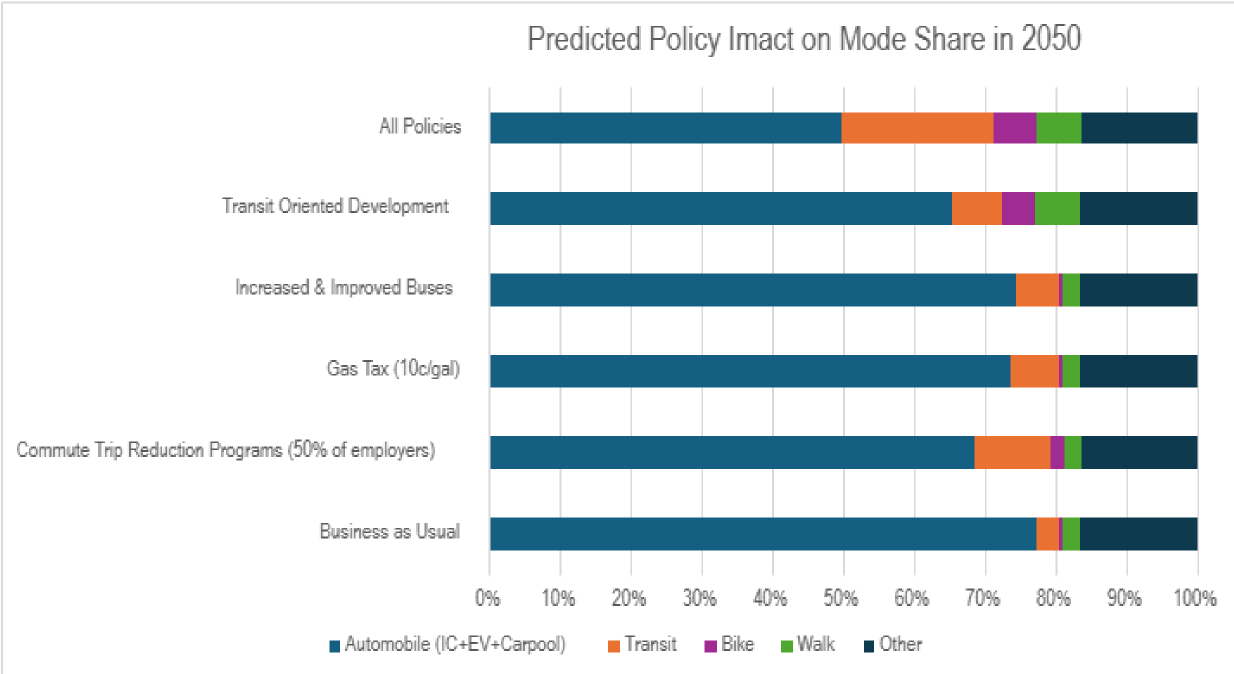


Figure 1. Mode share predictions based on the applied policies. "Other" includes taxicab, teleworking, and motorcycles, which remain constant.

Technology Pathway

When considering daily commutes, a possible pathway to carbon emissions reduction is the adoption of shared autonomous vehicles. Ridesharing decreases the number of personal vehicles needed by increasing accessibility of a low-time-cost transportation option. Autonomous vehicles lower the time cost even more by allowing transportation without a driver. A shared vehicle fleet lowers the barriers to adoption of new technologies like battery electric and hydrogen fuel cell vehicles due to their high up-front cost being shared and increasing the number of miles driven at a low per mile cost. There have been several studies done to see what the impact of a large fleet of shared autonomous vehicles would be on GHG emissions, but the conclusions have been complicated. Most studies show that carsharing reduces *personal* VMT and increases occupancy, but it also increases *total* VMT due to deadheading (miles travelled without passengers) and increased transportation demand [23]. Some of this is not significant in our analysis of daily commutes as transportation demand in this area is mostly inelastic.

By starting with the autonomous vehicle and personal vehicle drive-cycles recorded by Duan, Schockenhoff, and Koch there is some efficiency improvement inherent to autonomous vehicles due to their ability to optimize their driving patterns, set a maximum velocity and minimize acceleration [27].

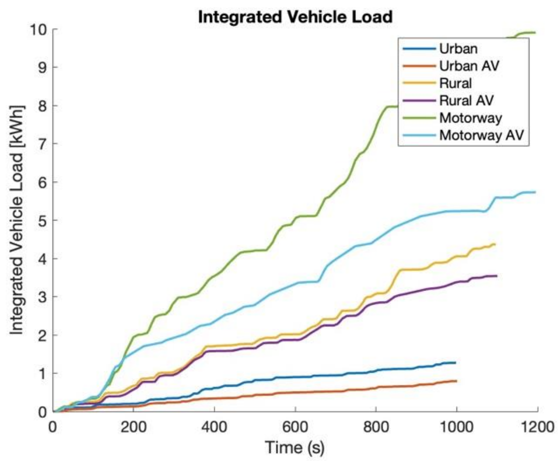


Figure 2. Vehicle load of the autonomous and non-autonomous drive cycles.

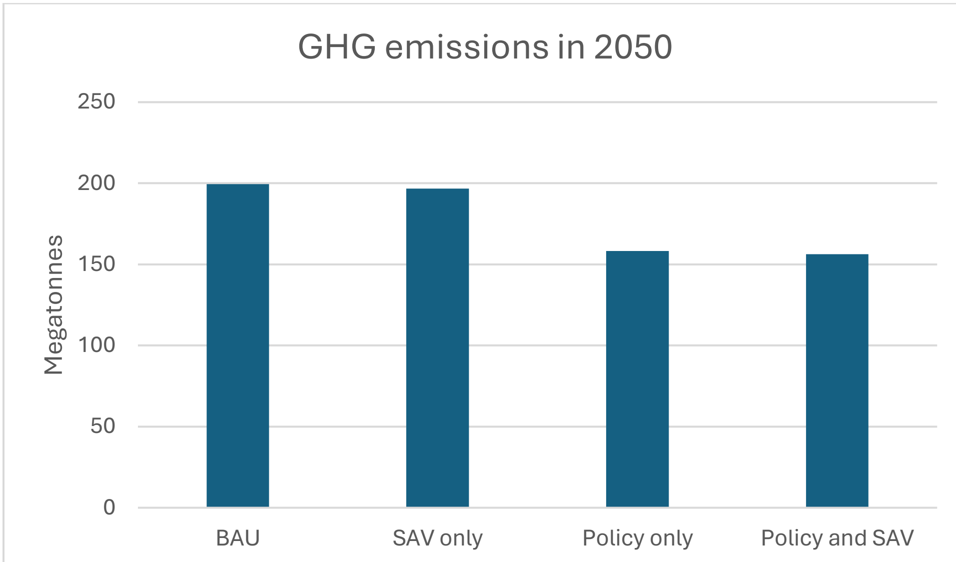
Comparing the autonomous and non-autonomous drive cycles, the autonomous vehicles efficiency factor of 0.715 for the urban drive cycle, 0.886 for the rural drive cycle, and 0.851 for the motorway drive cycle. In a census report from 2013, 78% of commuters in a principal city commuted by automobile, 89% of commuters in metro areas not in a principal city commuted by automobile, and 91% of commuters outside metro areas commuted by automobile [28]. According to this same report 33% of commuters live in a principal city, 54% live in metro areas, and 13% live outside metro areas. With these proportions, a weighted average of the commuter efficiency factor for non-autonomous versus autonomous vehicles would be 0.8108.

The final consideration for the implementation of shared autonomous vehicles (SAVs) is how much of the fleet would be electrified by 2050. According to Jones and Leibowicz, given 70% VMT shifted to SAVs and using optimized charging (charging during low demand and high renewable availability) 100% of SAVs would be electrified by 2050 [23]. The 70% VMT is further divided into passenger miles and deadheading with about 40% of VMTs occurring with no passengers [24]. Taking this into consideration, the average mode intensity of SAVs in passenger kilometers travelled does not improve very much since the penalty from deadheading approximately cancels the efficiency improvement on the drive cycle. This means that the greatest impact on GHG emissions from SAVs is the increase in EVs in the mode split for commuting.

The uncertainties in this calculation come from the grid mix, the percent VMTs driven by autonomous vehicles, and the percent EVs in the SAV fleet. The greatest sensitivity is the grid mix with a 50% improvement in GHG emissions from the grid changing the 1.4% improvement caused by the SAV fleet over the business-as-usual case to 5.8%. The VMT have very little sensitivity as changing the VMTs driven by SAV to 30% does not change the improvement from 1.4%. The same is true for changing the EV percentage to 50%. The main way to increase the impact of the SAV fleet on GHG emissions is by improving the grid mix.

Policy and Technology Impact on GHG Emissions

Figure 4. (below) Impacts of policies and SAV fleet implementation on the 2050 business as usual prediction.



In total, our advanced GHG reduction scenario decreased emissions by roughly 27% in 2050 relative to our business-as-usual scenario. A significant majority of the reduction is attributed to mode shifting, while impact of SAVs was modest due to conservative projections of grid carbon intensity improvement. If we assumed a more advanced reduction in grid emissions, we could achieve a 31% reduction.

Conclusion

Mode shifting is significantly more impactful on reducing emissions than more efficient driving with SAVs. With lower grid emissions, the SAVs would have a much greater impact.

One major critique of our methodology is assuming federal adoption of policies, whereas most of the transit policy initiatives studied are implemented locally. It is unlikely to assume that each policy will be applied equally, but rather concentrated in regions that are more densely populated. However, each assumption for the policy initiatives is based on case studies in specific cities or published literature, justifying their feasibility where there is support for implementation. Our policy focused on building out the use of existing underutilized transit infrastructure because the biggest challenge is the capital cost of transit projects. Transit projects in the US are estimated to cost 50% more and take far longer in the US versus similar projects in other countries, indicating the need for a more federal support for transit projects like administrative efficiency and funding priority over roadways [16, 25].

References

[1] Tippett R. What commuting statistics can't tell us about transportation use. Carolina Demography. 2015 Nov 14 [accessed 2024 Apr 10]. https://carolinademography.cpc.unc.edu/2015/09/14/what-commuting-statistics-cant-tell-us-about-transportation-use/#:~:text=Nationally%2C%20commuting%20accounts%20for%20only,passenger%20miles%20on%20public%20transit

[2] Summary of travel trends. 2017 National Household Travel Survey. 2017 [accessed 2024 Apr 10]. https://nhts.ornl.gov/assets/2017_nhts_summary_travel_trends.pdf

[3] Davis, Stacy C., and Robert G. Boundy. Transportation Energy Data Book: Edition 40. Oak Ridge National Laboratory, 2022, https://doi.org/10.2172/1878695

[4] Principal means of transportation to work. Principal Means of Transportation to Work. [accessed 2024 Apr 10]. https://www.bts.gov/content/principal-means-transportation-work

[5] Miller B. How many electric buses does your city have? (2022 edition). GovTech. 2022 Dec 16 [accessed 2024 Apr 10]. https://www.govtech.com/biz/data/how-many-electric-buses-does-your-city-have-2022-edition

[6] Average vehicle occupancy factors for computing travel time reliability measures. 2018 Apr [accessed 2024 Apr 12]. https://www.fhwa.dot.gov/tpm/guidance/avo_factors.pdf

[7] Eudy L, Jeffers M. King County Metro Battery Electric Buses. Zero-Emission Bus Evaluation Results. 2018 Feb [accessed 2024 Apr 12]. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/115086/zero-emission-bus-evaluation-results-king-county-metro-battery-electric-buses-fta-report-no-0118.pdf

[8] Energy intensity of light duty vehicles and motorcycles. Bureau of Transportation Statistics. 2022 Apr [accessed 2024 Apr 12]. https://www.bts.gov/content/energy-intensity-passenger-cars-other-2-axle-4-tire-vehicles-and-motorcycles

[9] Commute mode. Bureau of Transportation Statistics. 2022 [accessed 2024 Apr 24]. https://www.bts.gov/browse-statistical-products-and-data/state-transportation-statistics/commute-mode

[10] Vespa J, Medina L, Armstrong DM. Population projections for 2020 to 2060. census.gov. 2020 Feb [accessed 2024 Apr 24]. https://www.census.gov/content/dam/Census/library/publications/2020/demo/p25-1144.pdf

[11] Annual Energy Outlook 2022. Annual Energy Outlook - Energy consumption increases through 2050 as population and economic growth outweighs efficiency gains - U.S. Energy Information Administration (EIA). 2022 Mar 3 [accessed 2024 Apr 26]. https://www.eia.gov/outlooks/aeo/narrative/consumption/sub-topic-03.php

[12] Renewable Electricity Futures Study (Entire Report) National Renewable Energy Laboratory. (2012). Renewable Electricity Futures Study. Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/analysis/re_futures/

[13] Yip, Arthur, Christopher Hoehne, Paige Jadun, Catherine Ledna, Elaine Hale, and Matteo Muratori. 2023. Highly Resolved Projections of Passenger Electric Vehicle Charging Loads for the Contiguous United States: Results From and Methods Behind Bottom-Up Simulations of County-Specific Household Electric Vehicle Charging Load (Hourly 8760) Profiles Projected Through 2050 for Differentiated Household and Vehicle Types. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-83916. https://www.nrel.gov/docs/fy23osti/83916.pdf

[14] Automotive Trends Report. 2023 Dec [accessed 2024 Apr 24]. https://www.epa.gov/automotive-trends/highlights-automotive-trends-report

[15] Prospects for fuel efficiency, electrification and fleet decarbonisation. Global Fuel Economy Initiative. 2019 May [accessed 2024 Apr 24]. https://www.globalfueleconomy.org/media/708302/gfei-working-paper-20.pdf

[16] Puentes R, Brooks R. Move it: How the U.S. can improve transportation policy. Brookings. 2011 May 23 [accessed 2024 Apr 24]. https://www.brookings.edu/articles/move-it-how-the-u-s-can-improve-transportation-policy/

[17] Weingart E. Could Better Buses Fix your commute? The New York Times. 2023 Dec 7 [accessed 2024 Apr 26]. https://www.nytimes.com/interactive/2023/12/07/headway/bus-systems-routes.html

[18] Polzin SE, Maggio E. Public transit in america: Analysis of access using the 2001 National Household Travel survey. 2007 Feb 1 [accessed 2024 Apr 24]. https://rosap.ntl.bts.gov/view/dot/5568

[19] Litman T. Evaluating public transit benefits and costs. 2024 Apr 3 [accessed 2024 Apr 4]. https://www.vtpi.org/tranben.pdf

[20] Erhardt G, Hoque JM, Goyal V, Berrebi S, Brakewood C, Watkins K. Why has public transit ridership declined in the United States? 2022 Jul 19 [accessed 2024 Apr 24]. https://www.sciencedirect.com/science/article/pii/S0965856422000945?via%3Dihub

[21] Transit-oriented communities (TOC) policy. Metropolitan Transportation Commission. 2024 Feb 22 [accessed 2024 Apr 24]. https://mtc.ca.gov/planning/land-use/transit-oriented-communities-toc-policy

[22] Nathan McNeil and Jennifer Dill (2020), Revisiting TODs: How Subsequent Development Affects the Travel Behavior of Residents in Existing Transit-Oriented Developments, National Institute for Transportation and Communities (https://nitc.trec.pdx.edu); at https://ppms.trec.pdx.edu/media/project_files/NITC-RR-1240-Revisiting_TODs.pdf.

[23] Jones, E.; Leibowicz, B. Contributions of shared autonomous vehicles to climate change mitigation. Transportation Research Part D: Transport and Environment, Volume 72, 2019, Pages 279-298, ISSN 1361-9209.

[24] Henao, A., Marshall, W.E. The impact of ride-hailing on vehicle miles traveled. Transportation 46, 2173–2194 (2019). https://doi.org/10.1007/s11116-018-9923-2

[25] Aevaz R. Eno releases Major Report on U.S. transit costs and project delivery - the eno center for transportation. Eno Center for Transportation. 2021 Jul 30 [accessed 2024 Apr 24]. https://enotrans.org/article/eno-releases-major-report-on-u-s-transit-costs-and-project-delivery/

[26] Fossil vs. alternative fuels - energy content. The Engineering Toolbox. [accessed 2024 Apr 24]. https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html

[27] Duan, X.; Schockenhoff, F.; Koch, A. Implementation of Driving Cycles Based on Driving Style Characteristics of Autonomous Vehicles. World Electr. Veh. J. 2022, 13, 108. https://doi.org/10.3390/wevj13060108

[28] McKenzie B. Who drives to work? Commuting by automobile in the United States. 2015 Aug [accessed 2024 Apr 23]. https://www.census.gov/content/dam/Census/library/publications/2015/acs/acs-32.pdf

Appendix

Table A1. (below) EIA Table 1-9 EV LDV Overview 2023 .

Year	BEV	PHEV	Total_EV	FCEV	Total_LDV	EV_Percent
2011	29.688	64.674	94.362	0.127	231872.803	0.040696
2012	29.688	64.674	94.362	0.127	231872.803	0.040696
2013	85.706	108.946	194.652	0.177	237326.062	0.082019
2014	127.448	158.762	286.21	0.145	240796.578	0.11886
2015	194.84	196.657	391.497	0.204	248926.091	0.157274
2016	272.648	239.019	511.667	1.101	251219.004	0.203674
2017	353.348	368.288	721.636	4.623	257206.461	0.280567
2018	572.996	491.195	1064.191	5.922	259182.397	0.410595
2019	755.735	561.17	1316.905	7.626	261451.132	0.503691
2020	973.475	612.995	1586.47	8.19	259976.043	0.610237
2021	1421.96	774.913	2196.873	11.398	263152.322	0.834829
2022	2115.601	936.878	3052.479	13.862	263764.191	1.157276

Table A2. (below) GHG emissions estimate for commuter transportation in 2050 with only policies implemented. Total is 158.28 million tonnes per year.

Commute Mode	*Baseline (for reference)*	With Policy	Commuters (thousands)	1-way Commute Distance (km)	Mode Energy Intensity (kWh/PKT)	PKT	Emissions for 1 kWh Fuel (kg/kWh)	Annual Emissions (kg/year)	Annual Emissions (million tonnes/year)
Automobile (total)	*77.30%*	50.19%	93,698	19.54					
Drives self	*68.66%*	44.30%	82,699						
Carpool, total	*8.64%*	9.14%	17,066						
2-person	*6.38%*	7.34%	13,700						
3-person	*1.35%*	1.08%	2,010						
4+ person	*0.91%*	0.73%	1,356						
Automobile (IC)	*57.98%*	37.65%	70,274	19.54	0.701				
Drives self	*51.49%*	33.44%	62,415	19.54	0.701	609,669,083,973	0.247	105,414,218,706.25	105.41
Carpool, total	*6.48%*	4.21%	7,859						
2-person	*4.78%*	3.11%	5,797	19.54	0.350	56,628,522,109	0.247	4,895,648,780.23	4.90
3-person	*1.02%*	0.66%	1,231	19.54	0.234	12,022,500,690	0.247	692,912,789.60	0.69
4+ person	*0.69%*	0.44%	831	19.54	0.175	8,112,699,408	0.247	350,679,529.33	0.35
Automobile (EV)	*19.33%*	12.55%	23,425	19.54	0.184				
Drives self	*17.16%*	11.15%	20,805	19.54	0.184	203,223,027,991	0.351	13,107,123,219.06	13.11
Carpool, total	*2.16%*	1.40%	2,620						
2-person	*1.59%*	1.04%	1,932	19.54	0.092	18,876,174,036	0.351	608,721,219.84	0.61
3-person	*0.34%*	0.22%	410	19.54	0.061	4,007,500,230	0.351	86,156,245.57	0.09
4+ person	*0.23%*	0.15%	277	19.54	0.046	2,704,233,136	0.351	43,603,224.10	0.04
Public transportation (total)	*3.12%*	21.56%	40,241						
Bus (total) (Motor bus, Commuter, Trolley Bus)	*1.25%*	11.24%	20,977	16.56					
Bus (IC)	*0.94%*	0.94%	1,750	16.56	0.192	14,490,414,000	0.250	695,488,238.85	0.70
Bus (EV)	*0.31%*	0.31%	583	16.56	0.118	4,830,138,000	0.351	200,054,655.68	0.20
Light rail / Street Car	*0.18%*	2.69%	5,023	15.84	0.239	39,782,613,004	0.351	3,342,942,238.76	3.34
Heavy rail / Subway	*0.88%*	3.09%	5,760	15.84	0.143	45,621,321,764	0.351	2,284,890,023.45	2.28
Commuter rail / Railroad	*0.59%*	4.13%	7,707	40.91	0.233	157,650,676,739	0.250	9,188,785,999.89	9.19
Ferry boat	*0.04%*	0.14%	262	18.62	10.822	2,438,164,304	0.23	6,117,119,472.31	6.12
Taxicab (+DR) (total)	*1.16%*	1.16%	2,174	9.46					
Taxicab (+DR) (IC)	*1.15%*	0.00%	0	9.46	0.350	-	0.247	-	-
Taxicab (+DR) (EV)	*0.01%*	0.00%	0	9.46	0.092	-	0.351	-	-
Motorcycle	*0.10%*	0.10%	186.672	16.19	0.401	1,511,296,512	0.243	147,400,226.24	0.15
Bicycle	*0.50%*	6.04%	11283.85544	4.35	-	24,553,669,429	-	-	-
Walks only	*2.40%*	6.40%	11,947	1.90	-	11,373,551,616	-	-	-
Works at home	*15.20%*	15.20%	28,374	-	-	-	-	-	-
Total		100.7%	187,905					147,175,744,569	**147.18**
percent change from business as usual								-26.21%	-26.21%

Table A3. (below) GHG emissions estimate for commuter transportation in 2050 with only SAV fleet implemented. Total is 196.62 million tonnes per year.

Commute Mode	Percentage	With SAV	Commuters (thousands)	1-way Commute	Mode Energy Intensity (kWh/PKT)	PKT	Emissions for 1 kWh Fuel (kg/kWh)	Annual Emissions (kg/year)	Annual Emissions (million tonnes/year)
Automobile (total)	77.30%	77.30%	144,297	19.54					
Drives self	68.66%	68.66%	128,161						
Carpool, total	8.64%	8.64%	16,137						
2-person	6.38%	6.38%	11,904						
3-person	1.35%	1.35%	2,527						
4+ person	0.91%	0.91%	1,705						
Automobile (IC)	57.98%	17.72%	108,223	19.54	0.701				
Drives self	51.49%	15.73%	96,121	19.54	0.701	##############	0.247	162,340,455,221.10	162.34
Carpool, total	6.48%	1.98%	12,103						
2-person	4.78%	1.46%	8,928	19.54	0.350	87,209,298,427	0.247	7,539,417,939.43	7.54
3-person	1.02%	0.31%	1,895	19.54	0.234	18,514,942,850	0.247	1,067,102,513.04	1.07
4+ person	0.69%	0.21%	1,279	19.54	0.175	12,493,753,984	0.247	540,054,986.19	0.54
Automobile (EV)	19.33%	59.03%	36,074	19.54	0.159				
Drives self	17.16%	52.43%	32,040	19.54	0.159	##############	0.351	17,511,948,343.21	17.51
Carpool, total	2.16%	6.60%	4,034						
2-person	1.59%	4.87%	2,976	19.54	0.080	29,069,766,142	0.351	813,290,176.58	0.81
3-person	0.34%	1.03%	632	19.54	0.053	6,171,647,617	0.351	115,110,211.19	0.12
4+ person	0.23%	0.70%	426	19.54	0.040	4,164,584,661	0.351	58,256,674.27	0.06
Public transportation (total)	3.12%	3.12%	5,828						
Bus (total) (Motor bus, Commuter, Trolley I	1.25%	1.25%	2,333	16.56					
Bus (IC)	0.94%	0.94%	1,750	16.56	0.358	14,490,414,000	0.250	1,299,978,016.53	1.30
Bus (EV)	0.31%	0.31%	583	16.56	0.221	4,830,138,000	0.351	373,933,935.86	0.37
Light rail / Street Car	0.18%	0.18%	336	15.84	0.239	2,661,196,032	0.351	223,620,922.54	0.22
Heavy rail / Subway	0.88%	0.88%	1,643	15.84	0.143	13,010,291,712	0.351	651,605,095.72	0.65
Commuter rail / Railroad	0.59%	0.59%	1,101	40.91	0.233	22,529,518,349	0.250	1,313,149,598.02	1.31
Ferry boat	0.04%	0.04%	75	18.62	10.822	695,315,866	0.23	1,744,480,556.34	1.74
Taxicab (+DR) (total)	1.16%	1.16%	2,174	9.46					
Taxicab (+DR) (IC)	1.15%	1.15%	2,149	9.46	0.350	10,158,924,505	0.247	878,150,256.20	0.88
Taxicab (+DR) (EV)	0.01%	0.01%	25	9.46	0.080	119,226,552	0.351	3,335,623.11	0.00
Motorcycle	0.10%	0.10%	186.672	16.19	0.401	1,511,296,512	0.243	147,400,226.24	0.15
Bicycle	0.50%	0.50%	933.36	4.35	-	2,030,991,360	-	-	-
Walks only	2.40%	2.40%	4,480	1.90	-	4,265,081,856	-	-	-
Works at home	15.20%	15.20%	28,374	-	-	-	-	-	-
Total	99.8%	99.79%	186,273			##############		196,621,290,296	**196.62**
									-1.4%

Table A4. GHG emissions estimate for commuter transportation in 2050 with policies and SAV fleet implemented. Total is 145.34 million tonnes per year, which is a 27.13% reduction from 2050 business as usual.

Commute Mode	*Baseline (for reference)*	With Policy	With SAV	Commuters (thousands)	1-way Commute Distance (km)	Mode Energy Intensity (kWh/PKT)	PKT	Emissions for 1 kWh Fuel (kg/kWh)	Annual Emissions (kg/year)	Annual Emissions (million tonnes/year)
Automobile (total)	*77.30%*	50.19%	55.87%	93,698	19.54					
Drives self	*68.66%*	44.30%	46.46%	82,699						
Carpool, total	*8.64%*	9.14%	9.41%	17,066						
2-person	*6.38%*	7.34%	7.54%	13,700						
3-person	*1.35%*	1.08%	1.12%	2,010						
4+ person	*0.91%*	0.73%	0.76%	1,356						
Automobile (IC)	*57.98%*	37.65%	17.72%	70,274	19.54	0.701				
Drives self	*51.49%*	33.44%	15.73%	62,415	19.54	0.701	609,669,083,973	0.247	105,414,218,706.25	105.41
Carpool, total	*6.48%*	4.21%	1.98%	7,859						
2-person	*4.78%*	3.11%	1.46%	5,797	19.54	0.350	56,628,522,109	0.247	4,895,648,780.23	4.90
3-person	*1.02%*	0.66%	0.31%	1,231	19.54	0.234	12,022,500,690	0.247	692,912,789.60	0.69
4+ person	*0.69%*	0.44%	0.21%	831	19.54	0.175	8,112,699,408	0.247	350,679,529.33	0.35
Automobile (EV)	*19.33%*	12.55%	44.30%	23,425	19.54	0.159				
Drives self	*17.16%*	11.15%	39.35%	20,805	19.54	0.159	203,223,027,991	0.351	11,371,215,819.92	11.37
Carpool, total	*2.16%*	1.40%	4.95%	2,620						
2-person	*1.59%*	1.04%	3.65%	1,932	19.54	0.080	18,876,174,036	0.351	528,102,181.49	0.53
3-person	*0.34%*	0.22%	0.78%	410	19.54	0.053	4,007,500,230	0.351	74,745,712.41	0.07
4+ person	*0.23%*	0.15%	0.52%	277	19.54	0.040	2,704,233,136	0.351	37,828,413.10	0.04
Public transportation (total)	*3.12%*	21.56%		40,241						
Bus (total) (Motor bus, Commuter, Trolley Bus)	*1.25%*	11.24%		20,977	16.56					
Bus (IC)	*0.94%*	0.94%		1,750	16.56	0.192	14,490,414,000	0.250	695,488,238.85	0.70
Bus (EV)	*0.31%*	0.31%		583	16.56	0.118	4,830,138,000	0.351	200,054,655.68	0.20
Light rail / Street Car	*0.18%*	2.69%		5,023	15.84	0.239	39,782,613,004	0.351	3,342,942,238.76	3.34
Heavy rail / Subway	*0.88%*	3.09%		5,760	15.84	0.143	45,621,321,764	0.351	2,284,890,023.45	2.28
Commuter rail / Railroad	*0.59%*	4.13%		7,707	40.91	0.233	157,650,676,739	0.250	9,188,785,999.89	9.19
Ferry boat	*0.04%*	0.14%		262	18.62	10.822	2,438,164,304	0.23	6,117,119,472.31	6.12
Taxicab (+DR) (total)	*1.16%*	1.16%		2,174	9.46					
Taxicab (+DR) (IC)	*1.15%*	0.00%		0	9.46	0.350	-	0.247	-	-
Taxicab (+DR) (EV)	*0.01%*	0.00%		0	9.46	0.080	-	0.351	-	-
Motorcycle	*0.10%*	0.10%		186.672	16.19	0.401	1,511,296,512	0.243	147,400,226.24	0.15
Bicycle	*0.50%*	6.04%		11283.85544	4.35	-	24,553,669,429	-	-	-
Walks only	*2.40%*	6.40%		11,947	1.90	-	11,373,551,616	-	-	-
Works at home	*15.20%*	15.20%		28,374	-	-	-	-	-	-
Total				-					145,342,032,787	**145.34**
percent change from business as usual									-27.13%	-27.13%

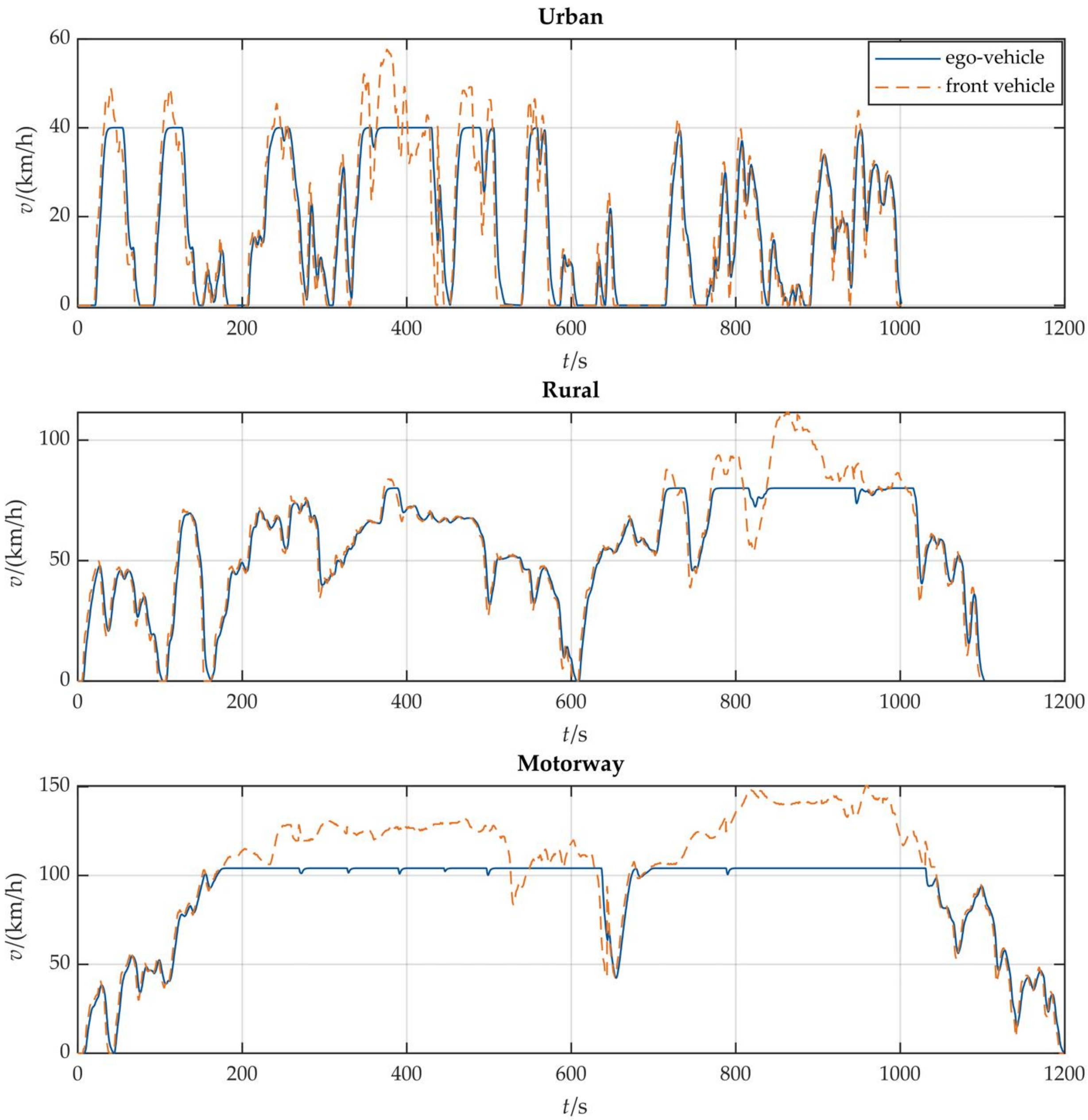


Figure A1. Drive cycles recorded by Duan, Schockenhoff, and Koch where ego-vehicle is a model of autonomous vehicle, and the front vehicle is non-autonomous [27].