REACHING ZERO CARBON TRANSPORTATION IN THE UNITED STATES: PATHWAYS AND MOVING BEYOND TRADITIONAL FRAMINGS

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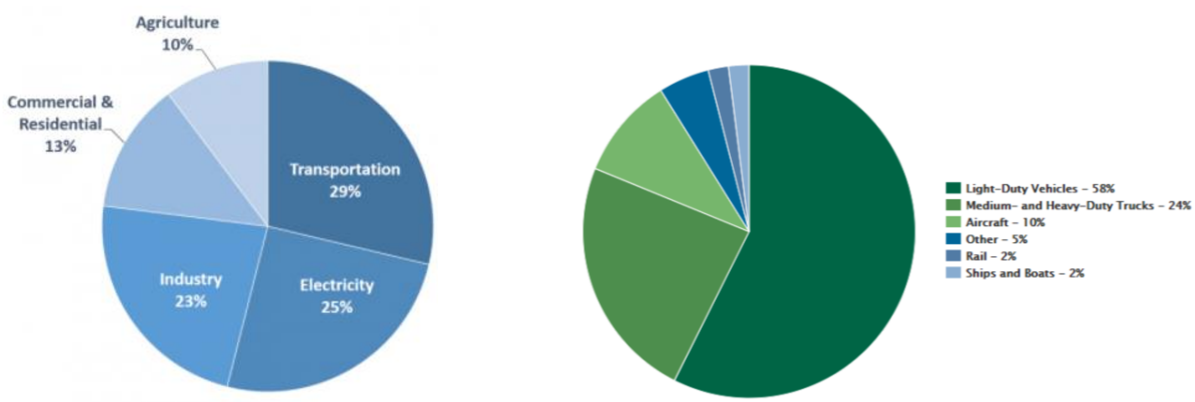
ABSTRACT

Climate change mitigation through decarbonization is an important and widely studied topic in the transportation field. Both technical and policy research place a strong focus on private vehicle electrification. Recent forecasts indicate a need for a nearly complete electrification of ground transportation by 2050. While vehicle electrification will certainly be a critical element of decarbonization, given current land use and travel patterns in the United States, uncertain adoption rates necessitate a many-faceted approach to meet our climate goals. New mobility alternatives, such as dynamic ride-sharing, may complement public transit in areas lacking the density to make traditional transit a net contributor to decarbonization. Population forecasts, a key input to transportation analysis, should not be taken as a given. Population stabilization could contribute a 85.42 GT reduction in GHG emisions between 2020 and 2050, a larger contribution than the estimated 11.87-15.68 GT reduction from vehicle electrification absent significant changes to the power grid. Finally, the impacts of urban expansion go well beyond increased travel. Biogenic emissions from land conversion have been found to contribute net emissions equivalent to 2.3% of fossil-fuel-based emissions from buildings and transportation in exurban cities.

Key Words: transportation decarbonization; vehicle electrification; long-distance travel; telework; population stabilization; land use

INTRODUCTION

Climate change, and associated environmental impacts, caused by the release of greenhouse gas (GHG) emissions is a major challenge. Transportation accounts for roughly 29% of total emissions in the United States (see Figure 1a). Within the transportation sector, light-duty vehicles (LDVs) comprise 58% of emisions (see Figure 1b). A wide variety of policy and technology measures are proposed in the literature to address the planet's climate crisis: alternative fuels (Wang et al. 2015); vehicle sharing, electrification, and automation (Milovanoff et al., 2020; Paul et al., 2011; Quarles and Kockelman, 2017 Chen et al., 2016; Jones and Leibowicz, 2019; Martin and Shaheen, 2011; Naumov et al., 2020; Quarles et al., 2019; Yan et al., 2020); public transit improvements (Casale and Mahoney, 2018; Chester and Horvath, 2009; Gallivan et al., 2015; Saxe et al., 2017; US DOT, 2010; Wellik et al., 2020); land use change (Ala-Mantila et al., 2014; Ewing et al., 2009, 2014; Ewing and Cervero, 2010; Glaeser and Kahn, 2010; Nichols and Kockelman, 2015; Wiedenhofer et al., 2013); and road pricing (Beevers and Carslaw, 2005; Cambridge Systematics and Urban Land Institute, 2009; Higgins et al., 2011; Nichols and Kockelman, 2014; Tirumalachetty et al., 2013). The COVID-19 response has illustrated the extent to which global action is possible in the face of crisis. Similar to the ongoing pandemic, a combination of technological, political, and logistical solutions are needed now, to address overheating the Earth's atmosphere.



(a) (b)

Figure 1. US GHG Emissions in 2019 by (a) economic sector and (b) transportation mode within transportation sector (US EPA, 2019)

A common means of structuring the discussion of transportation decarbonization is via the "three-legged stool" analogy (Ewing et al., 2009). Total GHG emissions are a function of the carbon intensity of the fuel (gCO_2/MJ), the fuel consumption efficiency of the vehicle (MJ/mi), and the demand for travel (total vehicle-miles traveled, or VMT). Historically, fuel efficiency standards (e.g., CAFE in the United States) have been reasonably effective in raising the efficiency of conventional internal combustion engine (ICE) vehicles. However, there is a limit to how far such standards can take us towards decarbonization, due to combustion-process limitations (Royal Dutch Shell, 2019) and fossil fuels' carbon content. Recent declines in the carbon intensity of U.S. power generation (see Figure 2) make vehicle electrification a key method for ground transportation's decarbonization. Policy research illustrates the dominant role that private vehicle electrification is anticipated to play in transportation decarbonization. Both Bhardwaj et al. (2020) and Axsen et al. (2020) recommend a mix of carbon pricing, emissions standards, and zero-emissions vehicle (ZEV) mandates as the ideal strategy. Recent multi-sector decarbonization studies for the United States also focus on vehicle electrification as the dominant strategy for the transportation sector (e.g., Zero Carbon America (Sustainable Development Solutions Network, 2020) and Net-Zero America (Larson et al., 2020).

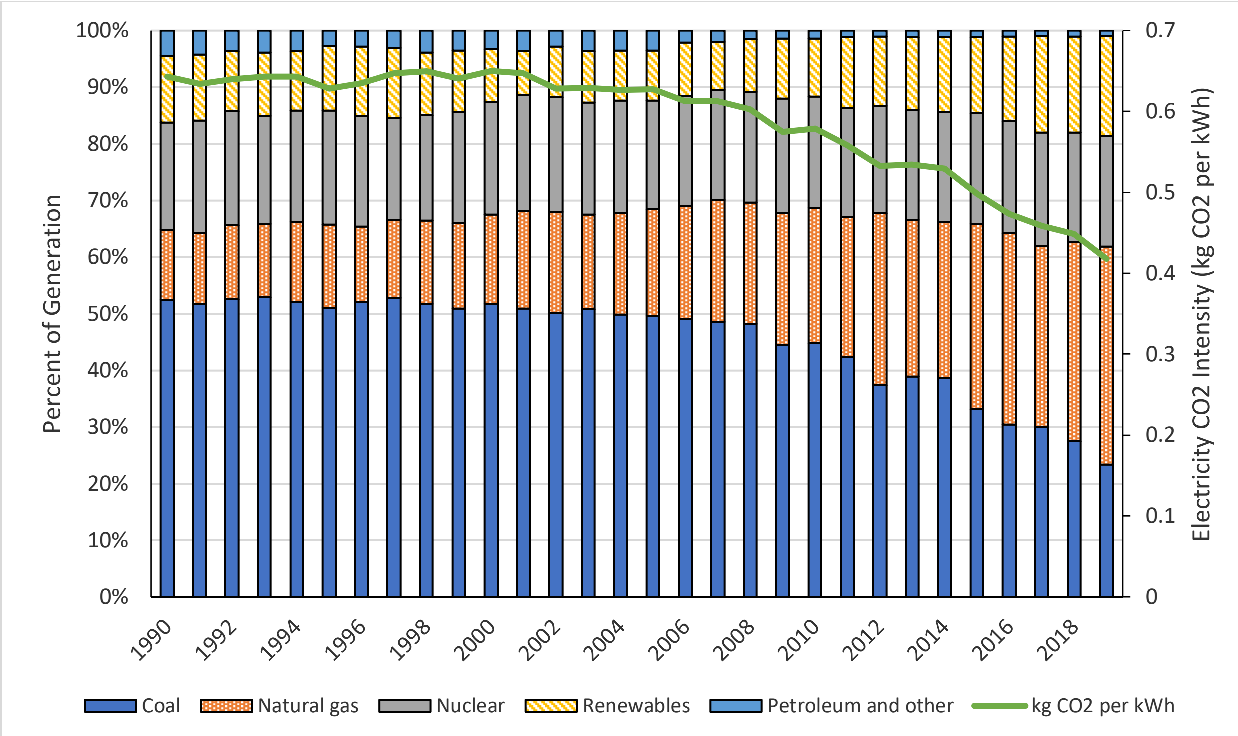


Figure 1. Historical United States Power Generation Sources and GHG Emissions (Data source: EIA, 2021)

The final leg of the 3-legged emissions stool is the demand for travel. Policies represented by this third leg are often termed as "smart growth" and include multi-modal planning, compact urban development, transportation demand management, and road and parking pricing (Litman, 2021). Transportation demand reduction is conceptually the simplest path to decarbonization. It does not require a new technology or the construction of new infrastructure: one simply reduces the aggregate amount of travel. However, it has been the hardest of the three legs to achieve results in. Due to space constraints, neighborhood and city design strategies, including upzoning and transit-oriented development (Nahlik and Chester, 2014), are not discussed in detail here. Moreover, new building, parcel, and neighborhood designs and land use mixes often require decades to implement at scale, at least in already-developed settings. Nevertheless, such practices will be critical to reducing a region's long-term GHG emissions (Leibowicz, 2017; Lewis et al., 2018), via standards for all new developments.

In this paper, we first outline limitations of the core strategies for transportation decarbonization identified in the academic literature and government plans: private vehicle electrification and public transit investments. We then focus in on two features of transportation - long-distance travel and telework - that have seen a particular focus recently due to the COVID-19 pandemic. Finally, we highlight a suite of decarbonization strategies that do not receive extensive discussion in the transportation demand analysis literature, framing the discussion using a standard flowchart in transportation demand modeling.

VEHICLE ELECTRIFICATION

Just as a stool will be unstable if one of its legs is weak, transportation decarbonization will be vulnerable to not achieving its goals if it relies on a single strategy. As noted above, previous research has highlighted the importance of a diverse policy mix to encourage vehicle electrification. However, while recognizing the need for policy diversity, it is also important to recognize the need for strategy diversity. Vehicle electrification will be a central component of transportation decarbonization in the United States, but it is unlikely to be sufficient alone (Milovanoff et al., 2020). Given the short history of electric vehicles (EVs) as an appreciable segment of the vehicle market, climate change planning for transportation has largely relied on *ex-ante* forecasts of market penetration. Such forecasts are highly uncertain (see Figure 3 for a range from one study by NREL) and are contingent on both political will to enact the necessary policies and public willingness to purchase these vehicles. The most ambitious NREL scenario (NREL-High) predicts a 2050 market penetration of 65%, or 83% with the addition of plug-in hybrid electric vehicles (PHEVs).

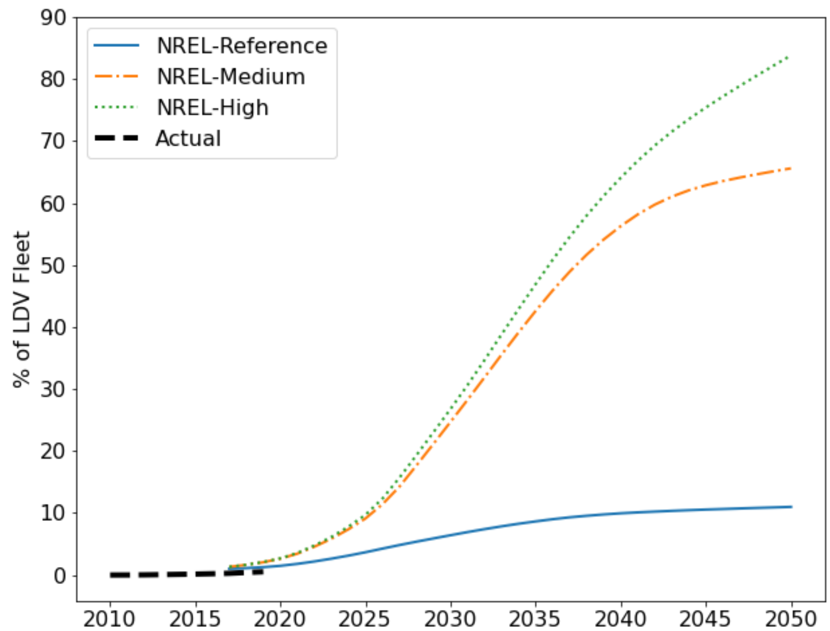
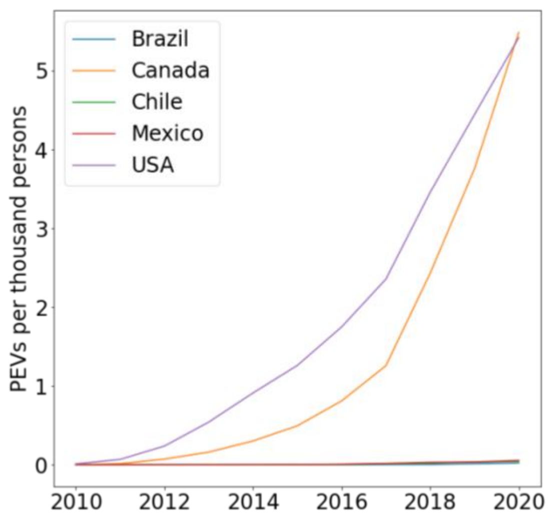


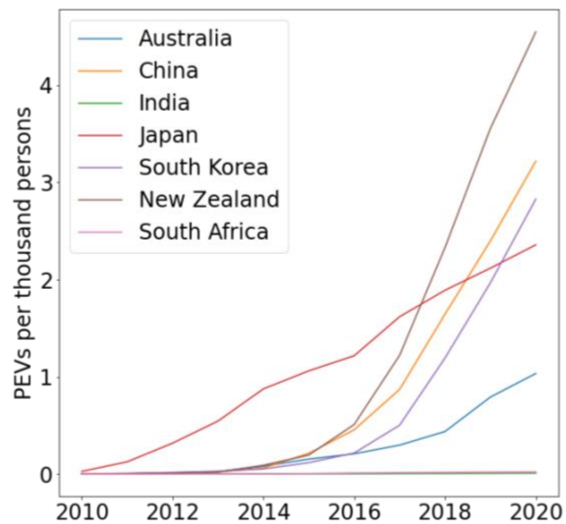
Figure 3. Historical and Forecasted EV Market Penetration (Data source: Mai et al., 2018)

Turning to where the markets needs to be to achieve a net-zero transportation sector, one recent study (America's Zero Carbon Action Plan) of pathways to deep decarbonization estimates that zero-emissions vehicles (ZEVs) need to represent 100% of LDV sales (as well as 80% and 60% of medium- and heavy-duty sales, respectively) in 2040 and 95% of the LDV stock by 2050 to meet a 1.5˚C target using only fuel shifting and electrification policy strategies (Sustainable Development Solutions Network, 2020). They predict vehicle electrification will induce a 20% increase to electricity demand above the *reference scenario*, which forecasts only a 20% sales share in 2050 for light-duty vehicles and no ZEV sales for other vehicle classes. In the most aggressive scenario in another multi-sector study of decarbonization in the US (Net Zero America), 96% of vehicles are battery-electric (BEVs) by 2050 (Larson et al., 2020). The IEA global net-zero emissions (NZE) scenario requires 70% of transport energy demand to come from electricity and hydrogen fuel by 2050 (IEA, 2020). All light-duty vehicle and nearly all heavy truck sales will need to be ZEVs by 2050 under the NZE scenario. Other research anticipates that meeting the transportation component of a 2˚C threshold on global warming with alone would require a fleet of 350 million BEVs (or about 90% of the US fleet) by 2050 (Milovanoff et al., 2020) and that the electricity required would represent half the national electricity demand if charging times are not coordinated (Muratori, 2018).

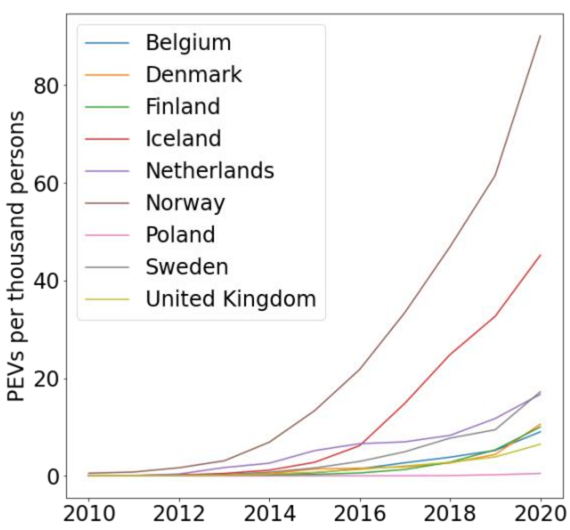
Given the above forecasts, Figure 4 outlines the current status of plug-in electric vehicle stocks around the world (battery-electric + plug-in hybrid electric). Stocks are normalized by population to ease comparison between countries. The US has seen a rapid increase in sales over the last decade but remains behind leading nations in northern Europe. Norway, with the highest penetration of PEVs, remains well below the levels required to meet the requirements outlined in the above studies.



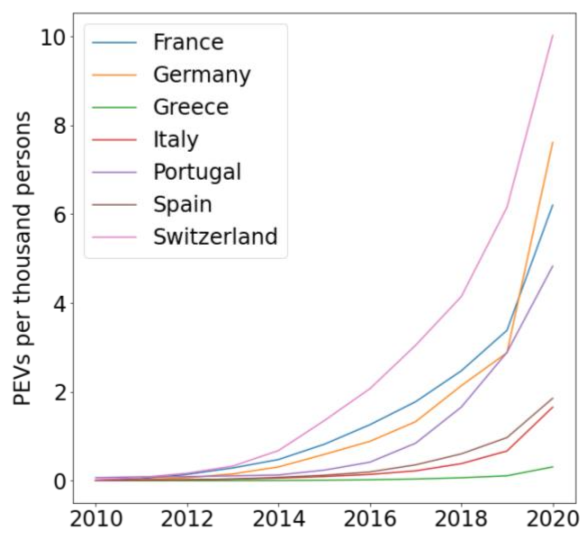
(a) North & South America



(b) Asia Pacific



(c) Northern Europe



(d) Central & Southern Europe

Figure 4. PHEV per Capita Stocks by Country (data source: (IEA, 2020))

In addition to electrification, forecasts generally assume an aggressive shift in the mix of power generation sources. The Net Zero America study assumes that wind and solar will be the dominant power generation sources by 2050, supplying half of U.S. electricity by 2030 and 85-

90% by 2050. As a point of reference, Figure 5 summarizes the current power generation mix for the countries shown in Figure 4 above.We highlight the US, as well as Canada and France as having comparable current rates of PEV market penetration. Both countries have less carbon-intensive generation mixes than the US - mostly hydro in Canada and nuclear in France. These comparisons reinforce the need for a substantial shift in the US transportation and electricity sectors in order to achieve alignment with the above forecasts.

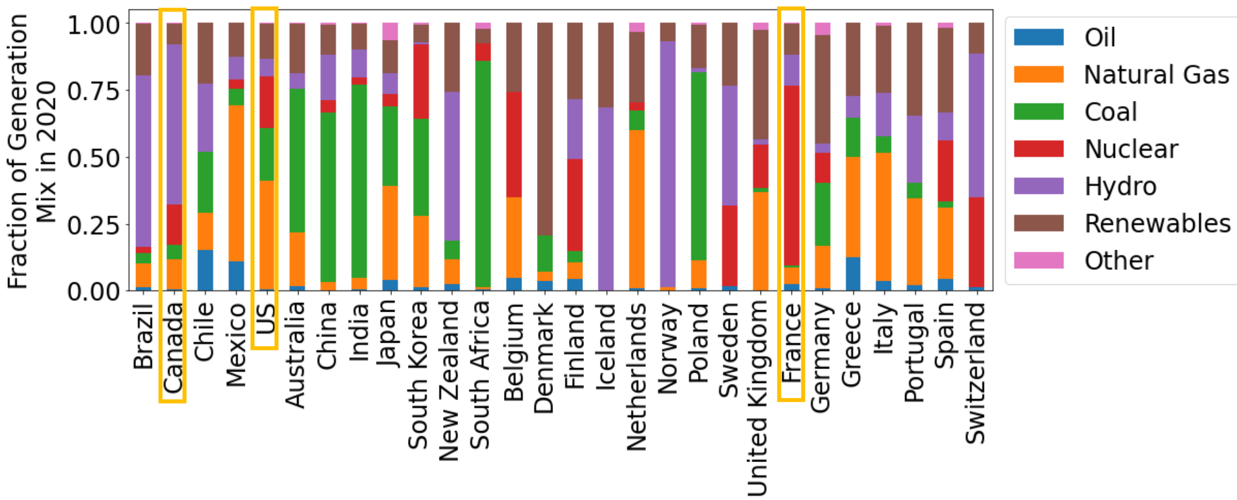


Figure 5. Power Generation Mix by Country (data sources: (British Petroleum, 2020; Ember, 2021)

PUBLIC TRANSIT

The role of public transit in decarbonization is complex for the United States. With some outlier cities, transit's share of total VMT is low in the United States (about 1% of total passenger-miles traveled (Polzin and Chu, 2011)). Increasing its share of travel would require massive investments and changes to land use, which is slow to change. Transit becomes cost-effective beyond a density of about 35 dwelling units per acre (Santasieri, 2014). The canonical comparison of the lifecycle GHG emissions for private vehicles and public transit is by Chester and Horvath (2009). They find that LRT and BRT are equivalent in their life-cycle GHG emissions to a single-passenger automobile when they have 13 and 21 passengers, respectively. A key metric for the feasibility of transit as a decarbonization strategy is then average vehicle occupancy (AVO). Figures 6 and 7 provide two perspectives to the public transit question. Figure 6 is based on an analysis conducted in Toronto, Canada and illustrates the temporal variation of transit bus GHG emissions. In the figure, crosses indicate the average GHG emission intensities for buses and the horizontal green bar highlights the interquartile range of private vehicle emission intensities. It is only during the off-peak evening that it becomes unattractive from a GHG emissions perspective to run buses. However, Toronto has among the highest transit ridership of North American cities (525M unlinked person-trips in 2019 (TTC, 2020)). Figure 7 compares the direct GHG emissions across transit systems in the US against a range of potential private vehicle occupancies. The average occupancy bus is slightly worse than a general-purpose trip by private vehicle.

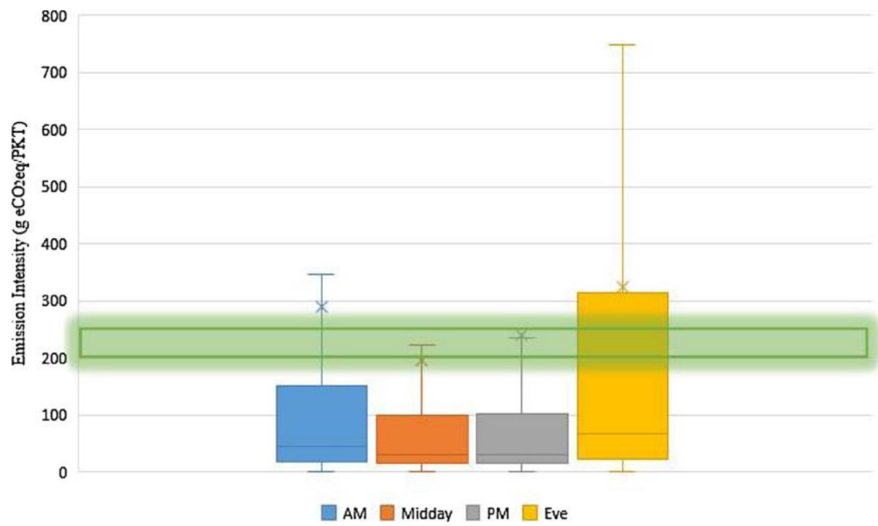


Figure 6. Emission Intensity (g CO2eq/PKT) for Transit Buses (Wang et al., 2018)

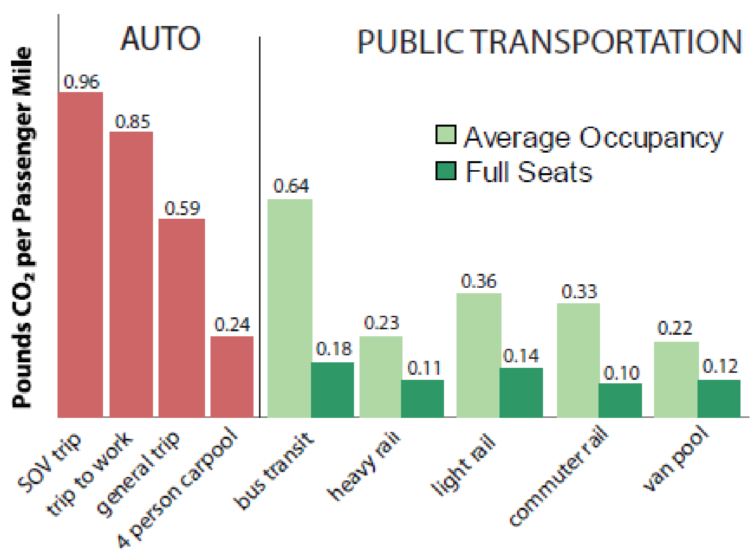


Figure 7. GHG Emissions per PMT Across Motorized Modes (Source: US DOT, 2010)

The poor performance of transit during off-peak periods is unlikely to be addressed to any reasonable magnitude through adjustments of scheduling or TOD. Rather, it is primarily a problem of vehicle right-sizing. The restricting element in this equation is the need for a driver in every vehicle, which necessitates the use of large vehicles on high demand routes. One potential strategy on the horizon is the use of fleets of shared autonomous vehicles, which are dynamically routed to match trips. These vehicles could be smaller than traditional buses and more efficiently serve regions of low demand density. While not yet in operations, simulation studies find reductions from dynamic ride-sharing (DRS) of roughly 20-25% for VMT and GHG emissions, relative to non-shared alternatives (Chen et al., 2016; Gawron et al., 2019; Jones & Leibowicz, 2019; Naumov et al., 2020). There are also potential synergies with the electrical grid through the use of vehicles as mobile storage devices (through vehicle-to-grid) or as mobile energy consumers to absorb excess power generation (Jones & Leibowicz, 2019; Khowaja et al., 2021).

It is also anticipated that DRS could reduce parking demand by 90%, freeing up land for other uses (Millard-Ball, 2019; Soteropoulos et al., 2019). Germany recently introduced legislation to allow AVs on German roads as early as 2022 (DW, 2021). The first vehicles will be shuttle buses and transit buses operating on set routes, but this legislation provides precedent for wider adoption of the technology.

LONG-DISTANCE TRAVEL

The year 2020 saw a significant decrease in GHG emissions relative to 2019 (see Figure 5). A significant component of this difference is a 48% reduction in emissions from the aviation sector relative to 2019 due to reduced international travel (Tollefson, 2021). Air travel is beginning to rebound (9.5% increase for March 2020-2021), but demand remains well below 2019 levels (Bureau of Transportation Statistics, 2021). Between personal and business trips, long-distance travel (50 miles one-way) accounts for about 43% of person-miles traveled in the United States according to the 2017 NHTS. Long-distance personal travel is usually for tourism and leisure: visiting family and friends or sightseeing. In a survey of Austinites, Li et al. (2020) found that 75.1% of respondents deemed their long-distance travel "impossible" to replace with a remote alternative. Decarbonizing long-distance travel could come in a variety of forms. First, through a reduction in the number of long-distance trips. Second, the carbon intensity of the chosen mode could be reduced through electrification or the use of alternative fuels. Finally, trips could be shifted to different - more efficient and lower carbon intensity - modes.

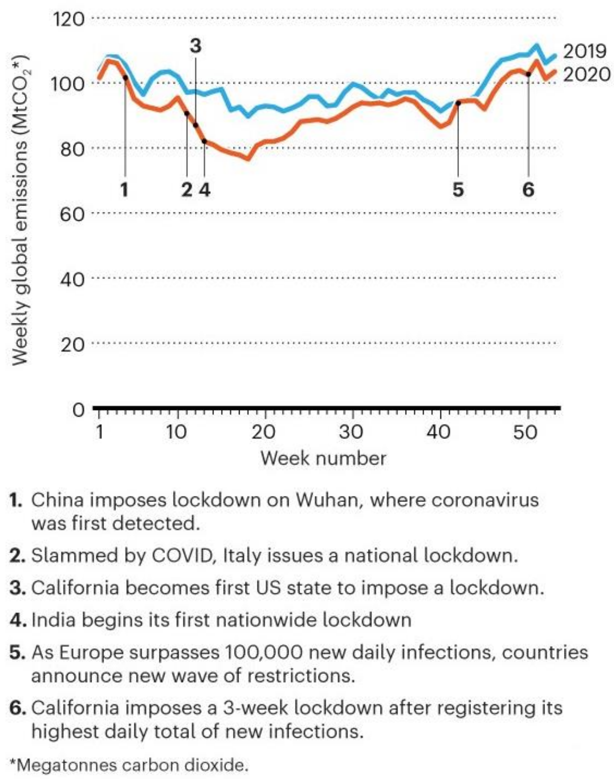


Figure 5. Weekly Global Emissions in 2020 Relative to 2019 (Tollefson, 2021)

Chester and Horvath (2009) provide a comparison of air travel and a standard ICE sedan. They estimate the lifecycle emissions per passenger-mile-traveled (PMT) for air travel at between 210 to 320 gCO_2eq (including supply chain and infrastructure). The lifecycle emissions for an average occupancy sedan are estimated at 360 gCO_2eq per PMT. The emissions for an average short-haul flight (i.e., UK to Europe) and average car trip are 315 and 247 gCO_2eq per PMT, respectively. Taken together, these results suggests that air travel is the preferred mode for long-distance trips from the perspective of decarbonization, but both modes being major generators of GHG emissions.

The simplest method of addressing the emissions of air travel would be to change the fuel source. There are several barriers to alternative fuel adoption that are distinct to the aviation industry. Mass and volume restrictions on the vehicle mean that the fuel source must have a high energy density, at least 42.8 MJ/kg (ASTM, 2015). For reference, biofuels have energy densities in the range of 15-20 MJ/kg (The Engineering ToolBox, 2009), and the most advanced lithium-ion batteries in production for surface vehicles have energy densities of about 260 Wh/kg (0.94 MJ/kg) (Reuters Staff. 2021). Researchers are working towards a goal of 500 Wh/kg batteries, or about 1.8 MJ/kg (PNNL, 2020). While a challenging engineering problem, advances are being made in the search for alternative fuel stocks. Between 2008 and 2019, more than 150,000 flights used biofuels, with the major fuel source being hydro-processed esters and fatty acid synthetic paraffinic kerosene (HEFA-SPK) (Le Feuvre, 2019). The IEA predicts a 10% market share for biofuels by 2030 and 20% by 2040 (Le Feuvre, 2019). Despite the relatively low energy density of batteries, electrification is occurring in the aviation sector. The eCaravan runs on a 750-horsepower electric powered by 2000 pounds of lithium-ion batteries (Metcalfe, 2020). It can fly about 100 miles and has a capacity of nine passengers. Similarly-sized planes under development are anticipated to have ranges of about 550-600 miles at a cruise speed of 325 mph (Bachmann, 2021).

For long-distance ground travel, vehicle electrification would reduce emissions relative to conventional ICE vehicles by roughly 56% with the 2016 electricity mix (Prevedouros and Mitropoulos, 2016; Bauer et al., 2016). A further modest reduction is possible with vehicle automation from its more efficient driving cycle (Fagnant and Kockelman, 2014; Taiebat et al., 2019). Automation is relatively feasible for long-distance trips, for which many drivers already employ cruise control technology. In general, traffic conditions are less complex on such trips than for short-distance trips that usually take place in mixed urban traffic. Overall, these benefits would bring down the per PMT lifecycle emissions of long-distance travel by automobile to perhaps 172 gCO_2eq (or 82% of the low-end estimate for air travel). Cho (2013) found that 90% of long-distance trips (over 50 miles) were made by personal vehicles in the United States. Lamondia et al. (2016) examined mode choices in Michigan for long-distance trips and predicted that over 25% of trips under 500 miles would switch to AVs.

TELEWORK

Telework is a policy that has seen increasing prominence with the development of better information and communication technologies (ICT) and most recently the COVID-19 pandemic. Telework can be defined as the replacement of commuting to a designated workplace with working from the home (or another nearby location). In theory, telework eliminates the need to travel and thus reduces the GHG emissions associated with travel. However, several complicating factors obfuscate its impacts. Workers are eliminating their commuting trips and therefore the emissions associated with fuel consumption. However, the net effect becomes less clear when ones considers total travel by the household and the potential for increased energy demands in the home for electricity and heating.

The first topic to address is whether telework can effectively replace all work activities. Many industries (e.g., healthcare, manufacturing, food services) require workers to be on-site and cannot be replaced by telework. The office provides other benefits beyond the exchange of information. It is also a venue for socializing and provides opportunities for serendipitous exchanges of ideas. As of 2017, only 5.2% of the workforce regularly worked from home (United States Census Bureau, 2018). During the height of the COVID-19 pandemic, it is estimated that 42% of individuals worked from home full-time (Wong, 2020). Many others worked from home during portions of the past year, such as teachers, social workers, and others forced to work from home due to public health restrictions, who may not be able to complete the full range of their duties in this environment. It is consistently estimated that only 37-40% of jobs in the United States can be done from home (Dingel and Neiman, 2020; Holgersen et al., 2020). These results provide an upper bound to the potential benefits of telework.

The demand for telework in a post-COVID economy remains uncertain. Many surveys were performed over the past year to predict this demand. One survey of 278 executives by McKinsey in August 2020 found these executives planned to reduce their company office space by an average of 30% (Lund et al., 2020). Another study predicted that one in four Americans would be working from home in 2021 (Upwork, 2020). A March 2021 study found that 85% of workers want to return to the office (AP News Staff, 2021). In a Canadian survey, 41% of workers stated a preference for splitting their time between the office and telework, while only 15% stated they would prefer to continue teleworking full-time (Mehdi and Morissette, 2021). The only clear result that can be drawn from these studies is that the future of telework is unclear.

The most frequently cited question about telecommuting is whether it induces additional travel. Workers may choose to make additional trips in response to the additional time made available by not having to commute to a workplace each day. Kim et al. (2015) found that the effect of telecommuting on trip induction partially depends on household vehicle ownership. Among households in Seoul, South Korea that have only one vehicle per employed member, it was found that telecommuting makes the vehicle available for use by other household members for commuting or other uses. Households that have sufficient vehicles do not see the same degree of rebound effect because other household members already have access to a vehicle to make their trips. They found that additional travel may occur, but they were unable to attribute its cause to telework. Their subsequent research set the magnitude of PMT induction from telecommuting at 2 km (Kim, 2017). However, this effect may not be as strong in the United States because vehicle ownership is much higher. Telework tends to increase trip lengths for nonmandatory travel (i.e., shopping and recreation) because dedicated trips are required whereas when working from the workplace individuals can make a side trip for shopping or recreation that may be shorter (Asgari et al., 2016; Shabanpour et al., 2018). Shabanpour et al. (2018) estimate that, if 50% of Chicago commuters could work from home, VMT would be reduced by only 0.69%.

An often overlooked aspect of the decarbonization impacts of telecommuting is its relationship with building use. Telework shifts GHG emissions to the home, where energy efficiency may be better or worse than the workplace. In general, office buildings have more efficient heating, cooling, and lighting systems that respond to occupancy. In contrast, a teleworker will often heat their entire home, despite it being largely unoccupied. Another consideration is that teleworkers generally only work from home a few days out of the week (O'Brien and Yazdani Aliabadi, 2020). As such, office space must still be heated for them throughout the week unless their employer has implemented a "hot-desking" strategy whereby employees are not provided with a dedicated workspace. O'Brien and Yazdani Aliabadi (2020) provide the following summary of studies that include both the transportation and building energy impacts of telecommuting. They concluded that the literature suggests a net overall reduction in energy use with telecommuting but that the impact grows smaller (and potentially reverses sign) as we gain more knowledge of rebound effects and broaden the scope of analysis. One of the factors absent from existing research on the topic is the impact of EVs. Figure 6 suggests that the widespread adoption of EVs would have a significant impact on the energy balance, particularly if there is a corresponding shift in the mix of power generation sources towards lower carbon-intensity alternatives.

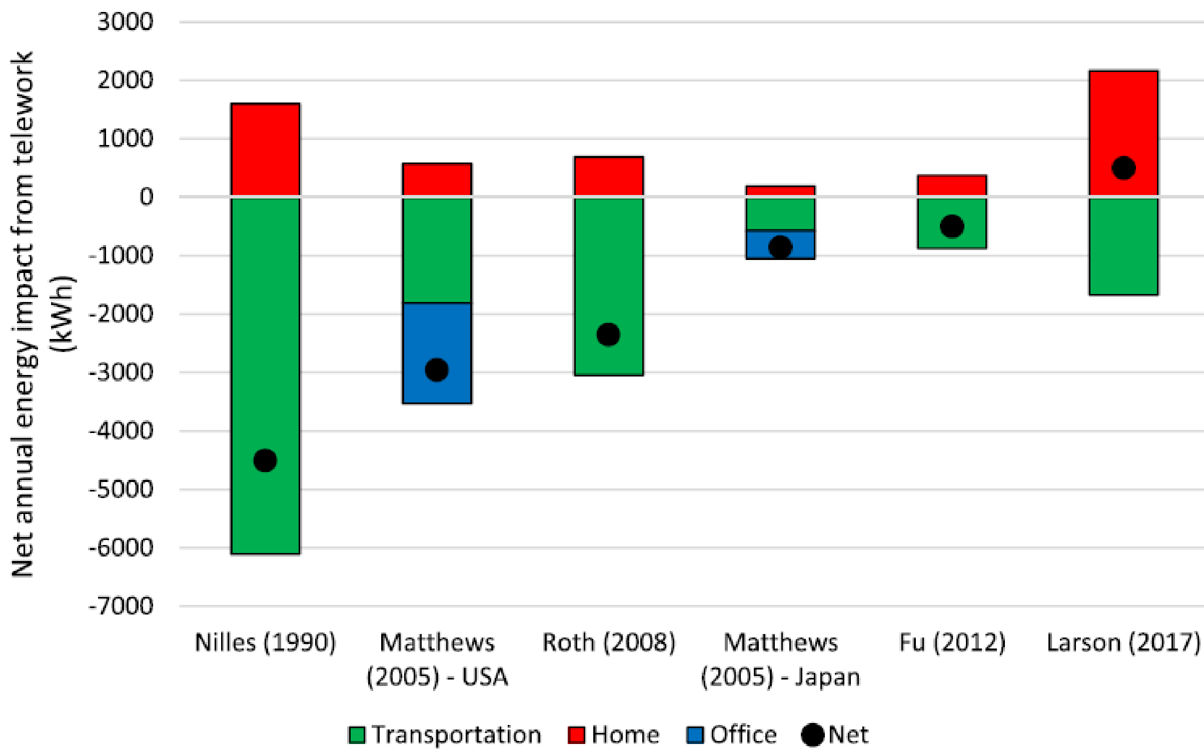


Figure 6. Estimated Impact of One-Day-Per-Week Teleworking vs. No Teleworking on Annual Energy (O'Brien and Yazdani Aliabadi, 2020)

Another aspect of increasing telework that may influence its potential to reduce aggregate emissions arises from workers moving to more suburban communities. The most recent study examined by O'Brien and Yazdani Aliabadi (2020), by Larson and Zhao (2017), captured the long-run effects of reduced travel costs with the widespread adoption of telework. They found that individuals chose to live in larger dwellings, further from their place of work. There is a long history of studying the effect of population density and urban form on energy demand and GHG emissions (Jones & Kammen, 2014; Leibowicz, 2020; Newman & Kenworthy, 1989; Nichols & Kockelman, 2014a; Sethi et al., 2020). Jones and Kammen (2014) found a 25% higher household carbon footprint in suburban communities than the urban core of the 50 largest metropolitan areas (50 tCO_2eq vs. 40 tCO_2eq). Nichols and Kockelman (2014; 2015) provide support for the finding that suburban built form is correlated with higher household GHG emissions.

Although there has been great hype about the end of urban life over the past year (Demsas, 2021), a recent poll found that seven in 10 people in New York, Los Angles, Chicago, Houston, Phoenix, and Arizona say they would prefer to stay in the city, with only 8% saying they would prefer to move to the suburbs (The Harris Poll, 2021). Interestingly, three in 10 suburban respondents stated they would prefer to move to a more urban setting. In our own recent survey conducted in April-May 2021, 54% of those who indicated an intention to move in the near future plan to relocate to a similar or closer distance to the CBD.

MOVING BEYOND TRADITIONAL FRAMINGS

To this point, the discussion has focused on conventional topics of transportation decarbonization. However, societal decarbonization requires us to take a broader, more holistic, perspective to the problem. A standard schematic of a transportation demand model (Figure 7) helps to frame the discussion for transportation modelers.

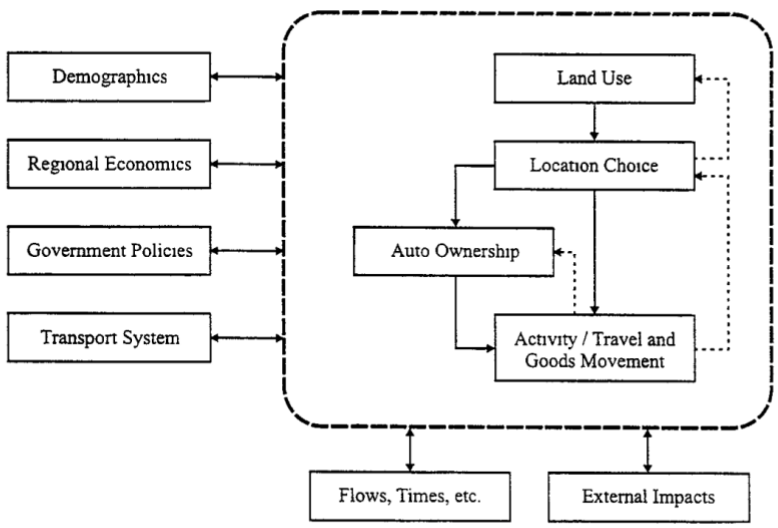


Figure 7. Idealized Integrated Modeling System

The components within the dotted circle are those typically endogenously defined in a transportation model. Vehicle electrification would be considered in the “auto ownership” model and telework in the “location choice” model. The public transit system is a part of exogenous “transport system” supply, with its demand being determined by trip generation and mode choice models under “Activity/Travel and Goods Movement”. Demographics includes, typically increasing, population forecasts for the study area. Measures to stabilize population growth would reduce the number of people seeking to travel and alleviate the need for technological solutions across sectors. Table 1 shows a cross-sectoral comparison of GHG emissions potential measured in global CO_2eq. While the magnitude of reductions is uncertain, the relative ranking of solutions remains informative. Population stabilization falls under “health and education”, as will be discussed below. Further, “land use” typically encompasses redevelopment and expansion as measures of density, which impact upon forecasted travel. However, Table 1 identifies major reduction and sequestration opportunities from land protection and changes in the food system.

Table 1. GHG Emission Reduction Potential of Key Sectors

Solution	**Transportation Connection**	**CO_2eq Reduction/ Sequestration (GT between 2020-20250)**
EVs (40% of LDV by 2050 and 100% of 2/3 wheel vehicles)*	Auto ownership	11.87-15.68
Public transit (22% to 35% adoption by 2050)	Transport system + activity/travel	7.51-23.36
Telepresence (including long-distance travel)	Location choice + Activity/travel	1.05-3.8
Grassland protection	Land use	3.35-4.25
Forest protection	Land use	5.52-8.75
Coastal wetland protection	Land use	0.99-1.45
Plant-rich diet	Land use	65.01-91.72
Food waste	Goods movement	87.45-94.56
Health + education (i.e., population)	Demographics	85.42

* Assuming current power generation mix. Power grid decarbonization reduces total GHG emissions by 115.9-247.59 GT CO_2eq in the Project Drawdown analysis.

Diet And Urban Biogenic Emissions

The most recent IPCC report estimated that a shift to a plant-based diet could save 0.7 to 8.0 GtCO_2eq per year globally (Shukla et al., 2019). Related to this change is a reduction in food and agricultural waste, which could reduce emissions by between 0.76 to 4.5 GtCO_2eq per year globally. Relating to transportation, a dietary shift is likely a more effective decarbonization strategy than addressing the supply-chain transportation impacts - only 11% of lifecycle GHG emissions (Weber and Matthews, 2008). Research suggests that adoption of a vegetarian diet, or even reducing meat consumption by 50%, is the most effective means of decarbonization of food consumption (Marlow et al. 2009; Heller and Keoleian 2015; Hedenus et al. 2014). Birney et al. (2017) estimated that food waste during production and transport represents 34% of total GHG emissions from the food lifecycle.

Urban biogenic emissisons comprise the net effect of land conversion less carbon sequestion from vegetation. The combination of these effects has seen minimal study to date. Milnar and Ramaswami (2020; 2021) computed the net effect for 11 US cities between 2006 and 2012. They found that biogenic emisions contributed a net positive effect in the exurban communities of Lake Elmo, MN and Rosemount, MN (equivalent to 1.5-2.3% of energy and travel-releated emissions, respectively), whereas in San Mateo, CA and Burlingame, CA a not offset is found of 1.5%. Related to food production, Bren d'Amour et al. predict that global urban expansion will occur on cropland that is 1.77 times more productive than the global average. While 80% of this cropland loss is expected to occur in Asia and Africa, it remains a critical concern in the US.

Population's Role

Decarbonization scenarios are generally framed through the lens of reducing aggregate GHG emissions through technology and policy measures that reduce the per capita production of GHG emissions. While not a typical topic of transportation research, policies affecting aggregate population will certainly affect transportation decarbonization.

Population projections by the United Nations (UN) suggest a population of 9.6 billion to 12.3 billion in 2100. An extensive research body suggests that the key to stabilizing populations is the education of women (Cunningham et al., 2001; Lutz, 2014). Globally, a woman who lacks any formal schooling gives birth to 4.5 children on average. Women who reach high school have only 1.9 children and those who attend 1-2 years of college have only 1.7 children on average. The effect of education on lower fertility is borne out throughout the literature dating from the 1980s (Bongaarts et al., 2012; Lutz and Skirbekk, 2017; Sell and Cochrane, 1981). These results provide support for the inclusion of local, state, and federal government policy that seeks to ensure the education of women both domestically and internationally as a part of any plan to address climate change.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Transportation is a key sector for the decarbonization of human activity. While vehicle electrification (plus renewable feedstocks in our power grid) is a key strategy, no one strategy will be sufficient. Decarbonization through increased public transit use requires a relatively high density and thus land development (or high road-user fees). It is unlikely that such densities can be achieved in a timely fashion (through land use reform) across most of the US to make public transit an effective decarbonization strategy in its current form. New technologies, such as DRS, that reduce marginal operating costs by removing the need for drivers may offer an alternative in such contexts. Long-distance travel and telework are critical transportation considerations that have been brought to the forefront of research through the COVID-19 pandemic. Technical restrictions in air travel impede its decarbonization but progress is being made to introduce alternative fuels and electrify this mode. The decarbonization potential of telework remains unclear and partly depends on building energy use and future development patterns.

There is a need to think more broadly and holistically about the factors encompassed by transportation. Vehicle electrification has encouraged synergies between the transportation and power sectors. It is imperative that these synergies continue to expand to include population stabilization and land conservation. Both are forecasted to be major contributors to societal decarbonization - an order-of-magnitude larger than EV adoption. These changes should be considered as inputs and alternative scenarios in regional transportation and land use analysis.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm the contribution to the paper as follows: study conception and design: Hawkins, J. and Kockelman, K.; Data analysis and interpretation of results: Hawkins, J; Draft manuscript preparation: Hawkins, J. and Kockelman, K. All authors reviewed the results and approved the final version of the manuscript.

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