Transportation Sector Report

A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study

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Acknowledgements

This report was prepared by the Cadmus Group and Evolved Energy Research for the Commonwealth of Massachusetts as part of the Decarbonization Roadmap Study.

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1 Executive Summary

The following technical report describes an analysis of sources of greenhouse gas (GHG) emissions from the Transportation Sector to provide insight into the technological, market-based, and policy-driven opportunities and barriers for decarbonizing those sources. The work was conducted by a team of researchers at the Cadmus Group, with additional support from the Resource Systems Group (RSG), working as part of the Massachusetts Executive Office of Energy and Environmental Affair's (EEA) 2050 Decarbonization Roadmap Study. This detailed analysis complements the high-level economy-wide analysis performed by Evolved Energy Research and published in the companion *Energy Pathways Report*.

The Transportation Sector produced 42% of statewide GHG emissions in the Commonwealth in 2017, the latest year with official emissions data. Emissions in this sector peaked at 33.8 $MMTCO_2e$ in 2005 but have since hovered around the 1990 baseline emissions level of 30.5 $MMTCO_2e$ between 2009 and 2017. Decarbonizing the transportation sector is a challenge with approximately 5 million vehicles on the road and thousands of - off-road and specialty commercial vehicles, aircrafts, and marine vessels, but is critical for achieving net-zero emissions economy-wide by 2050.

Light-duty vehicles (LDVs) – on-road personal cars and light trucks – are the source of 58% of total sector GHG emissions. Given the cost and scarcity of low- or zero-carbon drop-in replacement fuels, the current and growing availability of high efficiency battery-electric and other ZEV alternatives, and the practical necessity for residual 2050 emissions elsewhere in the economy, the LDV fleet must achieve near-zero emissions in the aggregate by 2050 in order for the Commonwealth to achieve its 2050 goal. Medium- and heavy-duty surface vehicles, which produce the next largest segment of sector emissions - approximately 30% in 2017 - must similarly be decarbonized but with a greater variety of low- and zero-carbon fuels and at a pace sensitive to the comparatively small number of largely commercially-owned vehicles to have near-zero residual emissions in 2050. Although multiple technologies exist in most vehicle classes that could functionally reduce emissions to near-zero levels within the Transportation Sector, battery-electric vehicles (BEVs) – due to comparatively low fuel cost and high drive-train efficiency – appear to be the most dominant, least-cost strategy (> 95% light-duty; > 50-60% medium/heavy-duty) for almost all modes, and for the vast majority of vehicle owners/operators.

Despite this opportunity, the turnover of vehicle stock represents a key limitation for the timeline of transition while ensuring that mobility remains cost-effective for vehicle owners and users. Although most vehicles turn over relatively quickly compared to other types of stock (e.g., major electric power plants, building envelopes), most vehicles will only be replaced twice between now and 2050. In addition, the broad adoption of electric vehicles raises new, cross-sector issues about access to charging and potential impacts on the electric power system that will need to be actively managed over time. Thus, policy interventions may be necessary to accelerate this transition, in order to meet interim and 2050 decarbonization targets and minimize upheaval, unintended consequences, stranded investments, and socioeconomic inequity.

Other emissions-reduction measures, including reduction in travel demand (measured as vehicle-miles traveled, VMT), deployment of hydrogen-fuel cell technology, and the use of low-carbon drop-in fuels (such as biofuels), may be helpful – even necessary in certain subsectors (e.g., biofuels for commercial long-haul aviation) – in achieving low sector emissions in 2050. However, due to cost, availability, implementation pace, or technical feasibility limitations, these measures do not appear capable of producing sufficient emissions reductions in a 30-year time frame to displace widespread electrification of on-road vehicles as the Commonwealth's primary Transportation Sector decarbonization strategy.

This transportation sector report is segmented into three distinct subsectors. The high-level findings for each subsector are presented below.

Light-Duty Sub-Sector (Chapter 5)

- A near full transformation of the Light Duty Vehicle (LDV) stock away from petroleum-derived fuels is needed to achieve net-zero statewide emissions by 2050.
- The average lifespan of LDVs in Massachusetts is 12-14 years, but some last much longer; there are a limited number of vehicle replacement cycles remaining prior to 2050.
- Battery-electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) offer the most promising long-term replacement technology for internal combustion engine vehicles (ICEVs). Additionally, plug-in hybrid electric vehicles (PHEVs) can help electrify a vast majority of vehicle trips in the near-term, as BEV markets grow, and beyond for certain vehicle and consumer categories that are less suitable for BEVs or FCEVs.[1]
- Most major automakers and several startups have already invested heavily in BEV technology and are expected to release new BEV models in the next three years. By 2025, over 400 BEV and PHEV models are expected globally. Costs of BEVs continue to fall, driven largely by battery cost reductions.
- In contrast, a shift towards large-scale hydrogen FCEV adoption among LDVs is unlikely in the near-term (3-5 years) given that no major automaker beyond Toyota, Hyundai, and Honda has announced a research and development pipeline for FCEVs.
- The current pace of EV adoption in the Commonwealth lags the pace necessary to achieve decarbonization targets compliant with the Global Warming Solutions Act (GWSA). Without new policy intervention (by the Commonwealth, California, or the federal government), less than 500,000 vehicles are projected to be electrified in 2030. In contrast, a pace consistent with meeting GWSA targets implies that over one million of the 5.5 million LDVs projected to be then-registered in the Commonwealth are electric in 2030.
- EV uptake is sensitive to the cost differential between EVs and ICEVs. Results of consumer choice modeling suggest that rebates of $2,000, $4,000, and $8,000 per BEV offered between 2025 and 2030 will increase new BEV sales in 2030 to an estimated 46%, 59%, and 79% of LDVs, respectively. Battery cost assumptions play an important role in determining the total cost differential.[2]
- Currently, most EV owners primarily charge their vehicles at home, although this trend may change as vehicles and charging stations proliferate, especially given the relatively high density of Massachusetts' built environment. Policy interventions may be needed to ensure easy and cost-effective access to publicly available charging infrastructure, especially for those without access to off-street parking.

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[1] BEVs are all-electric vehicles powered exclusively by electricity stored in on-board batteries. PHEVs have a dual powertrain that can utilize either electricity stored in on-board batteries or gasoline/diesel in an internal combustion engine. Collectively, this report refers to BEVs and PHEVs as "electric vehicles" or "EVs." Most FCEVs use gaseous hydrogen stored on-board in a fuel cell which converts hydrogen energy to electricity.

[2] Note the consumer choice model used in this analysis – MA3T – attempts to mimic human vehicle purchase decisions by accounting for both cost and non-cost factors.

Policy intervention will also likely be needed to moderate the impact of vehicle charging on the electricity grid.

- Reductions in vehicle-miles-traveled (VMT) align with ambitious decarbonization targets but are limited in opportunity.
- Housing densification policies were found to have only a modest potential impact on VMT because expected new development is small compared to the existing built environment (which is already relatively dense).
- Other policy interventions similarly targeting VMT reductions, such as roadway pricing, expanded transit infrastructure, or travel demand management, would have to be substantial in order to reduce VMT and emissions enough to materially contribute to sector-wide decarbonization by 2050.
- Even with higher levels of VMT reduction, near-complete LDV electrification remains essential to achieve decarbonization targets.

Medium and Heavy-Duty Sub-Sector (Chapter 6)

- Medium-duty and heavy-duty (MDHD) vehicles represent a relatively small population of individual vehicles and an even smaller number of discreet owners and fleet managers.
- Medium and heavy-duty transportation can be decarbonized though a transition to BEV, FCEV, or decarbonized liquid fuel technologies. There are opportunities and challenges for the application of each of these technologies to this sector. In general, on a national and global scale, decarbonized liquid fuels will likely need to be prioritized elsewhere in the economy and, in this sector, for aviation given the limited low carbon solutions for that sub-sector.
- Electric MDHD vehicle transit buses and some trucks – mostly those that service local delivery needs – are already available in modest volume. Additionally, several Class 8 electric and fuel cell vehicles have been announced – even pre-ordered in significant numbers by certain private fleets, such as Walmart - in the next few years.
- Long-haul freight trucks and certain vocational vehicles (such as fire trucks) are more challenging to electrify because of their high energy and power demands, constraints in terms of vehicle weight and load capacity. Electrification of these vehicle types is likely more expensive given their high power needs and the resulting potential for electricity distribution system impacts that would have to be internalized by vehicle operators as compared to using a high-cost-per-gallon low- or zero-carbon fuel.
- A current barrier to electrifying MDHD vehicles is the upfront cost of both the vehicles and charging infrastructure, which is considerably higher than for current diesel MDHD vehicles. However, electric versions of these vehicles tend to have lower operating and maintenance costs, especially when compared to use, instead, of high-cost-per-gallon low- or zero-carbon fuels to meet future emissions limits.
- Given their size and higher charging loads, the potential for electric MDHD vehicle charging to impact the electricity distribution system is higher than for electric LDVs. Therefore, the spatial and temporal concentration of these trucks is an important consideration in understanding their feasibility and cost.
- With electric powertrains for MDHD vehicles lagging behind the light-duty sector, opportunities to take advantage of MDHD fleet turnover before 2050 are more limited. Moreover, higher capital costs and the need for depot retrofits represent up-front barriers that generally do not exist for light-duty vehicles. This highlights that direct engagement with a relatively small population of fleet managers may be effective in easing up-front barriers and unlocking opportunities for rapid transition of those fleets.

Other Sub-Sectors: Aviation, Marine, Rail (Chapter 7)

- Due to power-density and range requirements, electric aircraft are not likely to play a major role in the aviation sector, even over the long-term.
- The widespread use of low- or zero-carbon liquid fuel in commercial aviation is likely required to maintain current, or even substantially reduced, levels of service.
- Aviation efficiency improvements are important for reducing cost and reducing the amount of decarbonized fuel imports required. These improvements are expected to approximately offset expected growth in air travel.
- Hydrogen, electric, and battery electric storage are the primary fuel options for decarbonizing transit and freight train services, as well as marine vessels and construction equipment. The long lifespan of these vehicle classes, however, make it unlikely that these sub-sectors will be deeply electrified by 2050. However, their contribution to total statewide emissions is extremely small and could be abated with relatively small deployment of high-cost decarbonized liquid fuels.

2 Introduction

2.1 Background and Purpose

This report describes modeling of the transportation sector conducted as part of developing the 2050 Decarbonization Roadmap Report and the Clean Energy and Climate Plan for 2030 (2030 CECP)*,* the latter being required under Massachusetts' Global Warming Solutions Act (GWSA).[3] [4] Its aim is to evaluate the technological transformation needed to achieve the decarbonization goals consistent with these statutory targets. Included in this report are an array of data and analyses that illustrate the challenges and solutions for decarbonizing Massachusetts' Transportation Sector. When feasible, the document benchmarks the Commonwealth with other jurisdictions. A range of strategies were evaluated to achieve this target over the next three decades. It aims to identify 30-year strategies for achieving these targets (reviewed in the Roadmap) and assesses what policies are needed in the near-term to put the Commonwealth on a path to achieving these targets (reviewed in the *2030 CECP*).

This report is one component of a study led by the Executive Office of Energy and Environmental Affairs (EEA) that explores options for deep reductions in GHG emissions. There are four other sector-based companion technical reports and one of these reports – the *Energy Pathways Report* – assesses economy-wide decarbonization strategies across the buildings, industrial, transportation, and energy supply sectors. The other companion reports focus on the buildings, land, and non-energy sectors.

The *Energy Pathways Report* uses an economy-wide energy optimization model to explore the range of possible future energy supply and demand portfolios – their technical make-up, system dynamics, and total system costs – capable of meeting the Commonwealth's 2050 climate goals. *The Energy Pathways Report* establishes a benchmark for technological transformation in the Transportation Sector needed for economy-wide decarbonization. It highlights that electrification of end uses – particularly those with electrification options in the near-term, such as light-duty vehicles – generally leads to lower overall costs than alternative approaches, such as using decarbonized fuels. This is largely due to the operational efficiency offered by electric powertrains and the low cost of clean electricity at scale as compared to relatively scarce and expensive liquid biofuels, and other low- or -zero-carbon synthetic fuels. Where electrification is costly or infeasible (e.g., aviation), hydrogen or decarbonized liquid fuels will be necessary to achieve decarbonization targets. In addition, mode shift and reductions in travel demand can also supplement these decarbonization strategies and continue to offer a range of co-benefits. However, electrification of transportation fleets emerges as the primary, least-cost, decarbonization strategy for nearly all travel modes particularly in the near- to mid-term.

This report discusses sub-sectors within the transportation sector, focusing on opportunities and barriers for electrification across a wide range of modes and duty-cycles. It evaluates how certain policy interventions can influence, accelerate, or ease fleet transformation, and highlights where new policy areas may be useful for

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[3] Executive Office of Energy and Environmental Affairs. Global Warming Solutions Act Background. https://www.mass.gov/service-details/global-warming-solutions-act-background

[4] Executive Office of Energy and Environmental Affairs (2020). Determination of Statewide Emissions Limit for 2050. https://www.mass.gov/doc/final-signed-letter-of-determination-for-2050-emissions-limit/download

guiding the transition and minimizing legacy costs in 2050. Several expert groups have explored viable paths forward for the Commonwealth's Transportation Sector. In 2018, the Commission on the Future of Transportation in the Commonwealth released the report *Choices for Stewardship: Recommendations to Meet the Transportation Future* to advise on future transportation needs and challenges in Massachusetts particularly in the 2020 to 2040 timeframe.[5] In addition to providing recommendations around modernizing transit infrastructure and managing land use appropriately, the report provided recommendations on methods to achieve GHG emission reductions, including a recommendation – consistent with the findings here – to phase out internal combustion engine vehicles (ICEVs) in new light-duty vehicle sales by no later than 2040.

The Transportation Sector is rapidly evolving. Even during the preparation of this report, several key developments took place. For example, in June 2020, California approved the Advanced Clean Truck (ACT) regulation, which requires manufacturers of medium and heavy-duty vehicles to meet increasingly aggressive sales requirements for electric vehicles.[6] The ACT regulation requires that by 2035 zero emission vehicles – including EVs and fuel cell electric vehicles – must be 55% of Class 2b-3 vehicle sales, 75% of Class 4-8 vehicle sales, and 40% of truck tractor sales. The ACT rule further requires that all drayage trucks be zero-emission by 2035 and all last-mile delivery trucks be electric by 2040. Additionally, in September 2020, California Governor Gavin Newsom signed an Executive order directing the California Air Resources Board (CARB) to promulgate regulations that would phase out light-duty ICEV sales in the state by 2035.

Massachusetts state law requires the Massachusetts Department of Environmental Protection (MassDEP) to set emission regulations that are equivalent to those adopted in California pursuant to that state's special preemption waiver authority under the federal Clean Air Act.[7] Massachusetts is currently working to implement the ACT rule. In July 2020, Massachusetts joined 15 other jurisdictions in a Memorandum of Understanding (MOU) that commits the state to develop an action plan that will speed adoption of medium and heavy-duty electric vehicles. This MOU sets a goal of at least 30% ZEV sales by 2030 and 100% by 2050. The vehicles targeted under this MOU include large pickup trucks and vans, delivery trucks, box trucks, school and transit buses, and long-haul delivery trucks. As CARB works to implement a phase-out of new light-duty ICEV sales by 2035, it is expected that Massachusetts would design and implement complementary regulations assuming California's preemption waiver remains effective.[8]

[5] Commission on the Future of Transportation (2018). Choices for Stewardship: Recommendations to Meet the Transportation Future. https://www.mass.gov/lists/choices-for-stewardship-recommendations-to-meet-the-transportation-future

[6] NESCAUM (2020) Multi-state medium and heavy-duty zero emission vehicle MOU. https://www.nescaum.org/documents/multistate-truck-zev-governors-mou-20200714.pdf

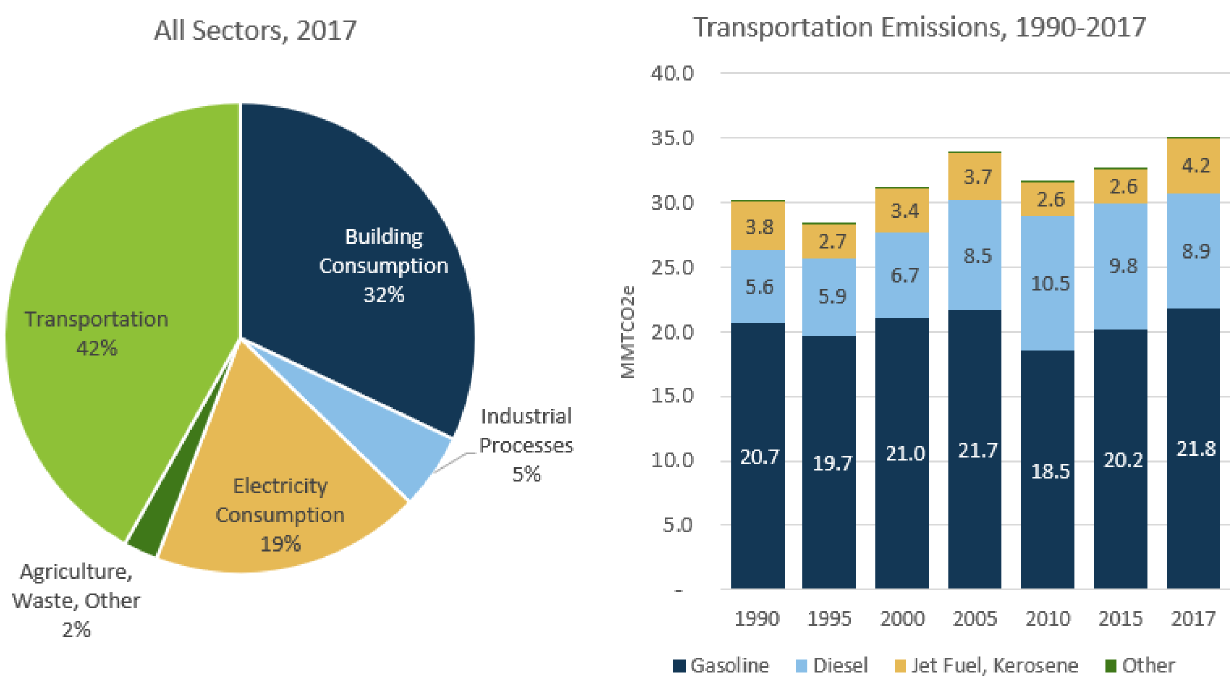
[7] M.G.L. c. 111 § 142K(a)" on Motor Vehicle Emissions Standards. Paragraph (a) provides that the Massachusetts Department of Environmental Protection "...shall adopt motor vehicle emissions standards based on the California's [sic] duly promulgated motor vehicle emissions standards of the state of California unless, after a public hearing, the department establishes, based on substantial evidence, that said emissions standards and a compliance program similar to the state of California's will not achieve, in the aggregate, greater motor vehicle pollution reductions than the federal standards and compliance program for any such model year." This section forms part of the basis for the Commonwealth's adoption of its Low Emission Vehicle Program, and California's Advanced Clean Trucks Rule.

[8] In September 2019, the federal government published a new rule regarding vehicle emissions standards that would have the effect of revoking California's preemption waiver. Together with twelve other state attorneys general, including the Massachusetts Attorney General, California has sued to challenge that revocation. (https://ww2.arb.ca.gov/resources/documents/carb-waiver-timeline)

2.2 Overview of Transportation Emissions in Massachusetts

At 42% of state-wide greenhouse gas (GHG) emissions as of 2017, the Transportation Sector accounts for the largest portion of the Commonwealth's emissions (Figure 1, left).[9] Population and economic growth underlie a long-term trend in increasing travel and freight demand in Massachusetts, challenging efforts to reduce emissions through incremental fuel economy standards. The recent emergence of e-commerce and ride hailing apps, as well as the COVID-19 pandemic, represent significant disruptions to these trends, adding uncertainty to long-term forecasts.

Figure 1. Massachusetts GHG emissions, economy wide (left) and transportation (right).



2.3 Decarbonizing Transportation in the Context of the Broader Energy System

A companion report to this current study – the *Energy Pathways Report* – assesses economy-wide decarbonization strategies across the buildings, industrial, transportation and energy supply sectors. The *Energy Pathways Report* analyzes the least cost pathways for meeting the Commonwealth's 2050 climate goals, including describing the technological transformation in the Transportation Sector needed for economy-wide decarbonization. This Transportation Sector report complements the *Energy Pathways Report* by addressing how such a technological transformation can occur, exploring how technical, human, and economic factors can facilitate such a transformation.

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[9] MassDEP (2020). Appendix C: Massachusetts Annual Greenhouse Gas Emissions Inventory: 1990-2017, with Partial 2018 Data. https://www.mass.gov/doc/appendix-c-massachusetts-annual-greenhouse-gas-emissions-inventory-1990-2017-with-partial-2018/download

The *Energy Pathways Report* demonstrates that decarbonizing transportation services will require the application of three generalized technological transitions:

1. Replacing conventional vehicles with battery electric vehicles (BEVs)
2. Replacing conventional vehicles with hydrogen fuel cell electric vehicles (FCEVs)
3. Substituting decarbonized fuels for petroleum-based fuels in internal combustion engine vehicles (ICEVs), with no-to-little drivetrain modification.

These transitions can be supported by vehicle efficiency gains and mode shifting, which reduces the demand for fossil fuels in the near term. Each of these transitions, even if pursued to a modest degree, will have significant impacts on energy systems. Vehicle electrification will substantially increase the demand for electricity at a time when the grid will transition to predominantly renewable generation. The growth of FCEVs will require the scaling of hydrogen production, particularly those methods that utilize renewable electricity, and hydrogen-specific distribution systems. The use of low carbon fuels will require carbon inputs, from biomass or carbon capture, from local, regional, and national stocks.

The *Energy Pathways Report* evaluated two decarbonization pathways relative to the transportation sector:

- **All Options:** a benchmark decarbonization case reflecting a high degree of LDV electrification; mixed electrification and fuel cell application to medium- and heavy-duty vehicles; and continued use of liquid fuels in the aviation sector.
- **Limited Efficiency:** Ground transportation assumptions are identical to the All Options pathway, though aviation is no longer assumed to improve in efficiency. This pathway was designed to primarily evaluate the impacts of low levels of building and industry efficiency.

The *Energy Pathways Report's* assumptions around ground transportation in each pathway reflect the current technological outlook in the sector and across pathways, did not generate significant differences in the energy supply sector. The rationale for this is described in further detail in the *Energy Pathways Report* and is supported by research presented later in this report. The report's cross-sector findings provide insight into the role of energy resources relevant to the transformations in the transportation sector, including electrification, hydrogen, and zero-carbon fuels.

Vehicle sale and stock for ground transportation are shown in Figure 2. Due to the current market growth and technological outlook of light duty BEVs, rapid electrification is assumed to be the predominant, least-cost strategy for this subsector. Based on current developments and trends, the sector is assumed to undergo a rapid market transformation between 2025 and 2040, nearing exclusive market share in the late 2030s/early 2040s. The medium and heavy-duty vehicle sector undergo a more delayed transition, with market share of both BEV and FCEV drivetrains widely replacing diesel and gasoline from 2030-2045. This split between BEV and FCEV reflects uncertainty with how these technologies will scale. Due to stock turnover lags, some (but very few) gasoline and diesel-powered vehicles remain in 2050 and contribute to residual statewide emissions. Total energy demand in ground transportation declines across all fuels (Figure 3) and subsectors (Figure 4) as electrification increases overall energy efficiency. The aviation subsector accounts for most emissions from non-road subsectors. Emissions from the aviation sector decline slightly through 2050 as the analysis assumed no meaningful electrification but did assume yearly efficiency gains, which are offset by increasing air travel demand, and increasing blends of low- and zero-carbon combustible fuels.

Figure 2. Massachusetts on-road transportation subsectors breakdown by sales (based on input assumptions) and the resulting stock and energy use by fuel. The percent of 2030 sales assumed to be electric is displayed on the first panel. Service demand (vehicle miles traveled) increases in all pathways, but final energy demand decreases due to the efficiency of electric drivetrains. In heavy duty trucks, long-haul trucking is assumed to transition to hydrogen while all short haul becomes battery electric.

Figure 3. Transportation energy demand modeled in the Energy Pathways Report. Note that the Limited Efficiency and All Options cases are identical for all fuels except for jet fuel which follows the reference pathway. The fuels listed on this figure are final demand and could be fulfilled by either fossil or low carbon resources: for example, in some scenarios a zero-carbon manufactured decarbonized *gasoline fuel emerges between 2040 and 2050 to meet the "gasoline fuel" demand.*

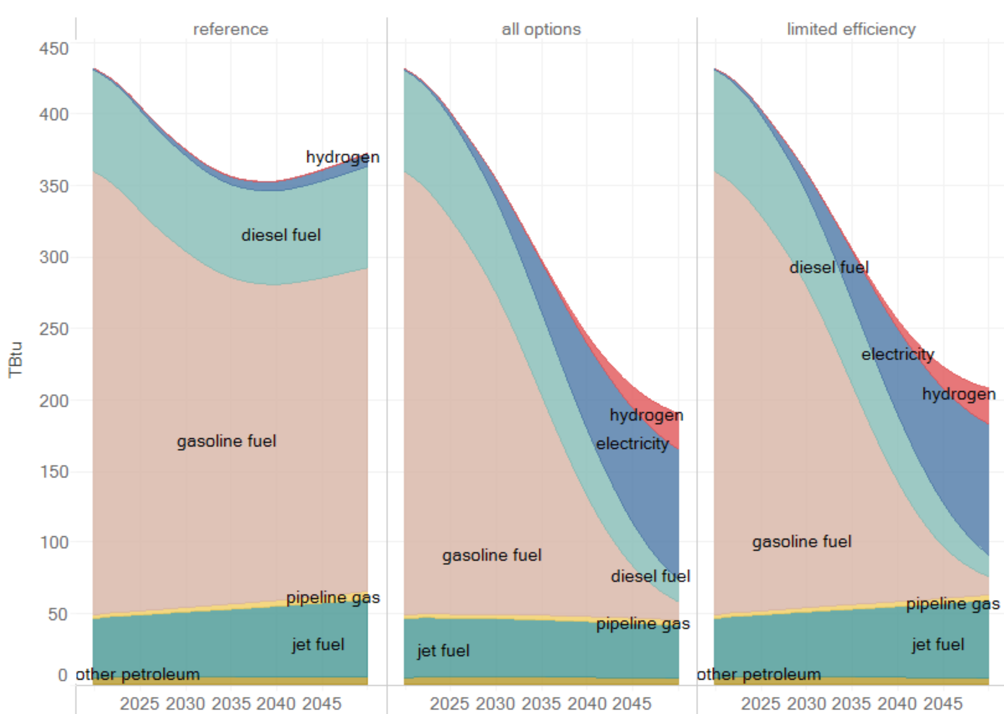
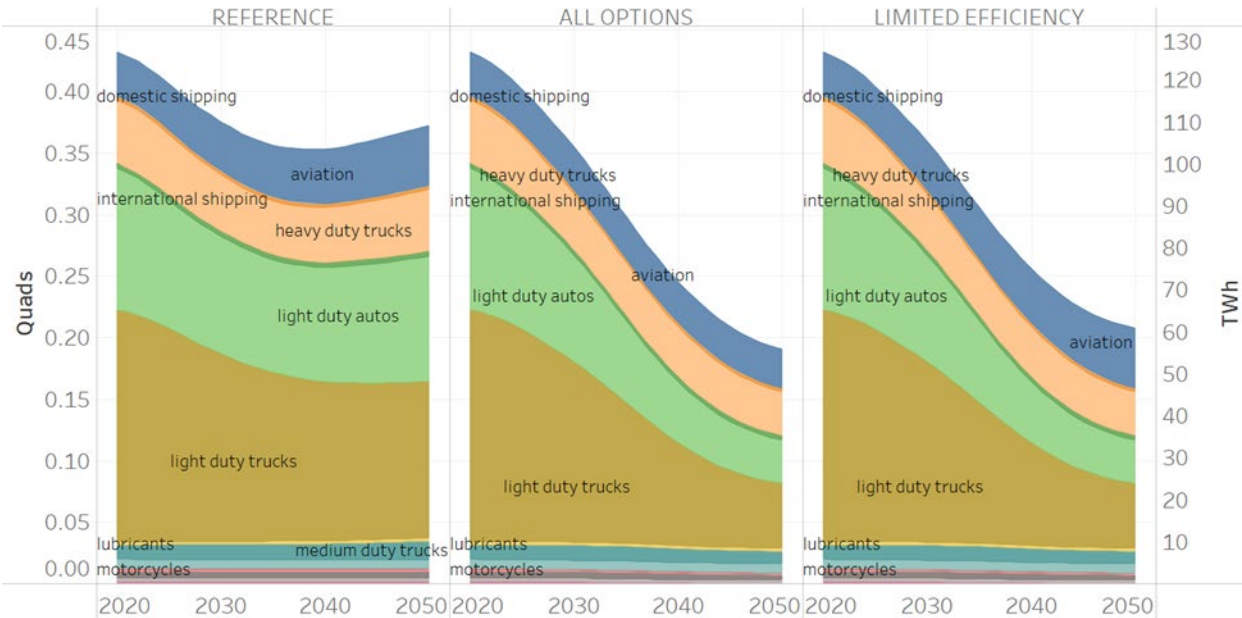


Figure 4. Transportation by sector demand modeled in the Energy Pathways Report. Note that the Limited Efficiency and All Options cases are identical for each subsector, except for aviation which follows the reference pathway.



Further details can be found in *Energy Pathways Report*. This analysis resulted in the following conclusions based on an assessment of system, fuel and operating costs:

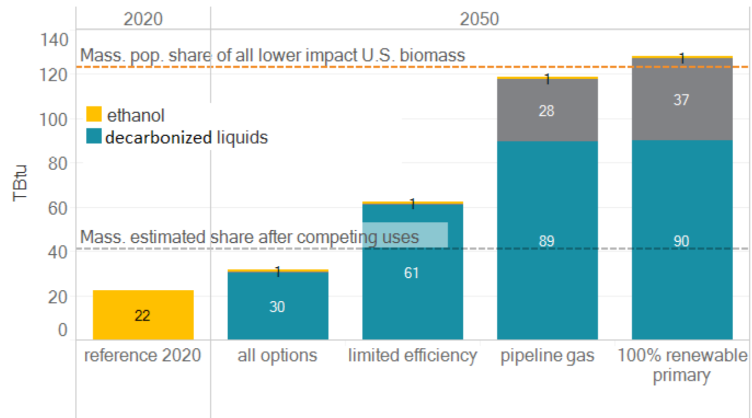
- Rapid electrification of light-duty transportation is a no-regrets, least-cost strategy for Massachusetts, including a target of 50% sales of zero emission LDVs by 2030.
- Electrification and hydrogen can meet the need of diverse medium and heavy-duty transportation end uses; however, this transition may lag that of LDVs.
- A limited quantity of residual liquid petroleum fuels used in on-road transportation is compatible with reaching net-zero emissions in the light-, medium- and heavy-duty subsectors.
- Aviation will be reliant on decarbonized liquid fuels. Subsequently, efficiency improvements are important for reducing cost and reducing the amount of decarbonized fuel imports required.

The role of decarbonized liquid fuels deserves additional explanation and is further detailed in the *Energy Pathways Report*. Two general types of decarbonized fuels were considered in this analysis. The first is captured carbon-derived fuels that react hydrogen with captured carbon to generate a liquid fuel. The analysis found that while a small amount of these fuels was generated within Massachusetts, they were generally expensive.

The second are biomass-derived fuels, mostly imported from outside Massachusetts. The Net Zero America Project at Princeton University identified 12 quads as the limit on U.S. biomass production without new land under cultivation for purpose grown energy crops. This estimate includes land currently used for corn ethanol and was derived from the 2016 U.S. Department of Energy Billion Ton Study Update. After competing uses of these resources (chemicals and bioplastics) are accounted for, Massachusetts' population-weighted share for this is approximately 41 TBtus per year. The practical implications of this are shown in Figure 5.

Currently, Massachusetts imports approximately 22 TBtus of ethanol as a gasoline additive. With electrification, the demand for the additive shrinks to 1 TBtu in 2050. This is replaced by a demand for decarbonized diesel, jet fuel, and other petroleum products that is met by approximately 30 TBtus of bioenergy in the All Options pathway. While this replaces and exceeds the current ethanol demand, it is still below Massachusetts's population-weighted share of biomass. Due to the higher jet fuel demand in the Limited Efficiency case, a significant amount of low carbon imports would be required, leading Massachusetts to exceed its population-based share. This would imply an unsustainable level of biomass consumption. It follows that lower levels of electrification in the ground transportation sector would require higher levels of such decarbonized fuels to achieve emissions reduction targets. This dynamic pertains to other sectors as well, particularly for building heat.

Figure 5. Massachusetts imports of decarbonized liquid hydrocarbons. These fuels are made in the rest of the U.S. (or internationally) for export to Massachusetts and the rest of the Northeast using technologies that imply carbon neutrality. The orange dashed line represents Massachusetts's population share of U.S. biomass production that limits purpose-grown feedstocks to the same land footprint currently used for ethanol production, plus all available crop wastes and residues. The grey dashed line is the share after taking into account competing uses such a chemical feedstocks. Carbon-neutral liquid fuel imports in 2020 are the corn ethanol currently used in Massachusetts.

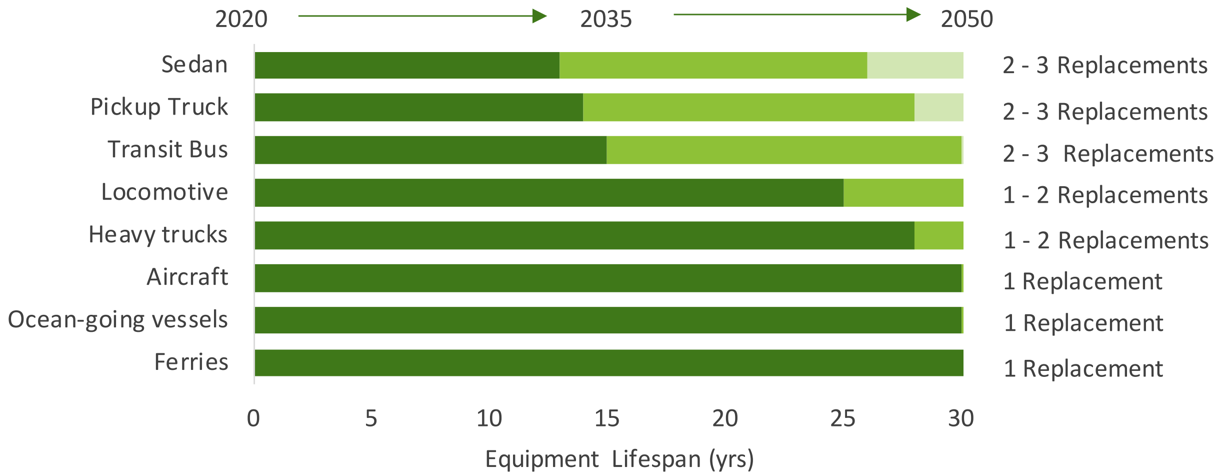


Massachusetts' imported decarbonized energy is 9 TBtus below its population weighted share in the All Options Scenario (Figure 5). As framed by Figure 3 and Figure 4, this data indicates that only a small decline in EV and FCEV adoption, and continued reliance on ICE vehicles would likely cause Massachusetts to exceeded its population-weighted share of imported bioenergy fuels. While additional demand can be met with synthetic fuels generated from captured carbon, these fuels are currently expected to be expensive compared to electricity and the costs of widespread electrification.

2.4 Sector-Wide Considerations

As indicated above, in order to achieve net-zero emissions in 2050, the Transportation Sector must be almost fully decarbonized in the next 30 years. An important consideration for this transition is the life cycle of equipment. Depending on the vehicle type and application, life cycles can range from 10-30 years (Figure 6). As shown, certain sub-sectors – such as LDVs and transit buses – turn over much faster on average than other subsectors – such as aircraft. In some categories, vehicles purchased in 2020 will still exist in 2050, locking in a technology for the long-term. This implies that waiting for technological alternatives, with the hope of lower costs, incurs a risk of those technological alternatives not panning out and likely increasing costs in the long term. The rest of this document explores how to facilitate those transitions while considering these constraints.

Figure 6. Illustrative replacement cycles of various vehicle types.



3 Organization of Document

The chapters in this report are organized by the following:

- **Chapter 4: Methodology.** Describes the approach for quantitative and qualitative analysis.
- **Chapter 5: Light-Duty Sub-Sector.** Describes modeling conducted on vehicle and fuel technologies used in Class 1 and 2a vehicles purchased by households and firms.
- **Chapter 6: Medium-Duty and Heavy-Duty Sub-Sector.** Describes modeling conducted on vehicle and fuel technologies used in Class 3-8 vehicles purchased by government and private fleet operators.
- **Chapter 7: Other Sub-Sectors: Aviation, Marine, Rail.** Describes modeling conducted on non-road sectors including Transit, Aviation, Marine, and Rail.
- **Chapter 8: Travel Demand Reductions and Mode-Shift Strategies.** Describes modeling conducted on non-technology solutions to reducing transportation emissions.

The key research questions addressed in this report are shown in Table 1. These research questions were chosen by the project team to help guide the analysis. This report focuses heavily on technology options for decarbonizing LDVs, given the sub-sector's outsized contribution to transportation emissions, relative market maturity of decarbonization technologies compared to other transportation sub-sectors, and potential for catalyzing cost reductions in other, more difficult to decarbonize sub-sectors. Additionally, among all technologies, a key focus of this report is on electric vehicles (EVs). EVs refer to plug-in electric vehicles, including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). Fuel cell electric vehicles (FCEVs) and other decarbonization strategies such as biofuels, electrofuels, mode shifting, and reduction in VMT are also discussed.

Table 1. Research questions addressed in this report.

Sub-Sector	Short Description	Questions	Methodological Approach
LDV	Battery-electric and plug-in hybrid electric vehicle incentives	What is the impact of various incentives on adoption of battery electric and plug-in hybrid electric vehicles?	Market Acceptance of Advanced Automotive Technologies (MA3T) model
LDV	LDV EV subsidies	How does the cost of incentivizing EVs change as the EV market matures and moves from early adopters to late adopters?	MA3T model
LDV	Electric Vehicle Supply Equipment (EVSE) Deployment	What is the impact of various EVSE incentives and charging availability on adoption of battery electric and plug-in hybrid electric vehicles?	MA3T model
LDV	EVSE	What level of publicly available EVSE infrastructure is needed to support EV targets?	MA3T model, EVI-Pro Lite, and Census data
MDHD Vehicles	Heavy-duty Decarbonization	What technologies are available for medium/heavy-duty decarbonization? What is the timing of economically viable fuels that will lead to deep decarbonization?	Market characterization and outlook
Aviation, Rail, Marine	Non-Road Decarbonization	What technologies are available for aviation decarbonization? By what policy mechanisms can the Commonwealth decarbonize aviation?	Market characterization and outlook
Personal Mobility	Mode shift	What is the impact of various mode shift strategies?	Energy and Emissions Reduction Analysis Tool (EERPAT) model

4 Methodology and Tools

This chapter describes the methodology used in this report, which includes a variety of models, tools, datasets, and literature to gain insights into decarbonization options of Massachusetts' transportation sector between now and 2050. No single model is capable of addressing all topics related to decarbonization of the Commonwealth's transportation sector. Therefore, the Cadmus team developed a set of models that give the necessary resolution on geography, technology, and policy, while providing flexibility to address new topics as they arise. Figure 7 provides a flow diagram of the modeling. The four key models, shown in green in Figure 7, include:

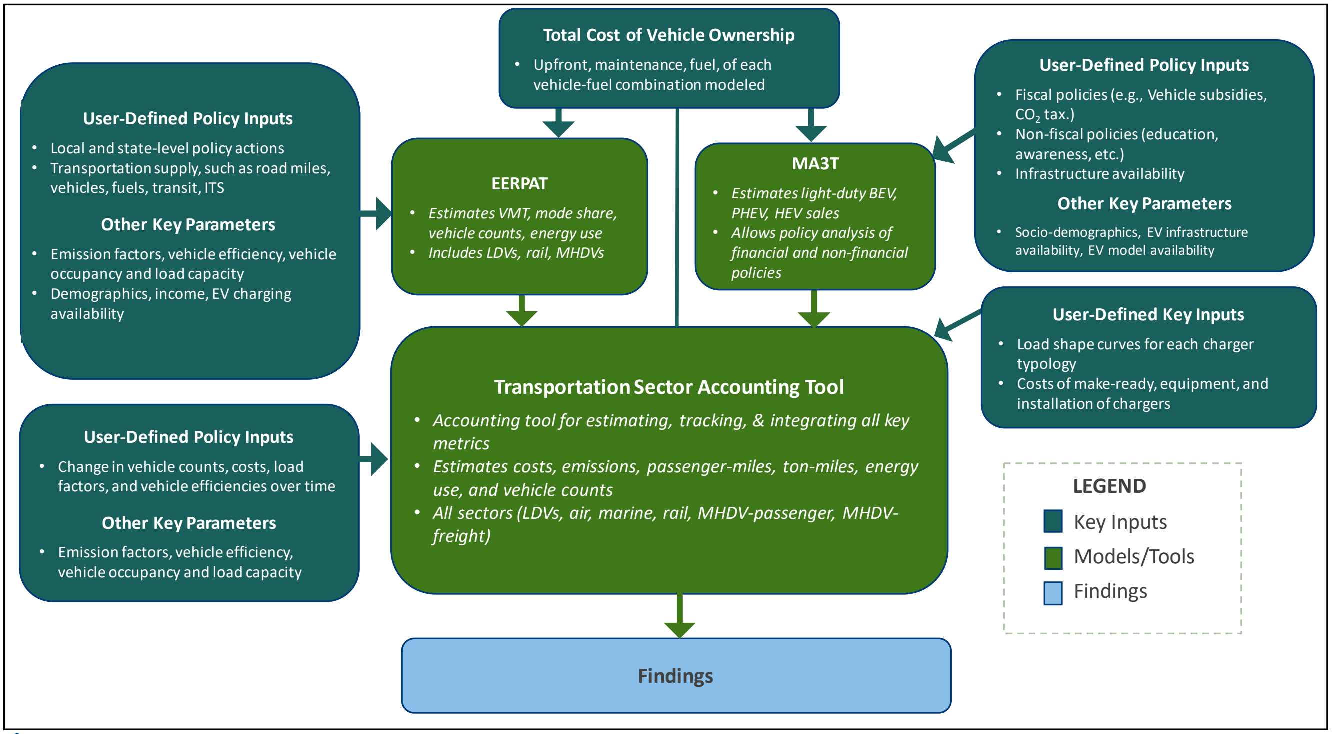
- Market Acceptance of Advanced Automotive Technologies (MA3T);
- Energy and Emissions Reduction Analysis Tool (EERPAT);
- Transportation Sector Accounting Tool (TSAT);

For each of the four models, Cadmus developed a Reference Case and several Policy Cases to evaluate sector wide trends. As shown in Chapter 3, the Reference Case is generally aligned with the Reference case established in the companion study to this – the *Energy Pathways Report*. The minor differences between Reference Cases are due to difference in modeling platforms. The Transportation Sector Accounting Tool serves as the central "hub" for all sub-sectors and models/tools, integrating output from various tools, models, and data sources. Table 2 provides a description of the models and summarizes the purpose of each model in this report.

Table 2. Summary of models used in this report.

Model *(Developer)*	Description	User-Interface	Purpose for this Report
MA3T Model *(Oakridge National Laboratory)*	• Estimates the "S-Curve" adoption of **light-duty Electric Vehicles** between today and 2050 at the county-level; • Shape of S-curves will be influenced by a range of exogenously assumed inputs.	Excel	• Used to model light-duty EV sales at the county-level under a variety of policy scenarios; • Account for characteristics and preferences of both early and late adopters of EVs.
EERPAT *(Federal Highway Administration)*	• Multi-step model that characterizes travel and ownership projections of **household vehicles**, **trucks**, **urban transit, inter-city transit, commercial vehicles**, **rail** at a sub-state level; • Model steps include: (1) define households and associated polices, (2) characterize vehicles, (3) calculate VMT and emissions, (4) balance VMT with travel costs, and (5) estimate non-household travel and emissions.	R language	• Used primarily to model travel demand (VMT), mode shift strategies, medium/heavy-duty vehicles and bus sales under a variety of policies.
Transportation Sector Accounting Tool *(Cadmus)*	• Accounting tool that will provide representation of **all subsectors within Massachusetts's Transportation sector**, including light-duty, medium-/heavy-duty, aviation, marine, rail, and non-road. • Estimates emissions, energy use, passenger-miles, ton-miles, cost-per passenger-mile (from driver perspective), cost-per ton-mile (from driver perspective), for all modes.	Excel	• Used to estimate, aggregate, and track key metrics over time associated with all modes. • Used to ask "what if" questions about assumed changed in technology and fuels on emissions and energy use.

Figure 7. Flow diagram of modeling and analysis.



4.1 MA3T Model

4.1.1 Model Overview

MA3T is a consumer choice model that estimates adoption of conventional and alternative fuel LDVs between 2015 and 2050. MA3T inputs and outputs are at the state-level for all 50 states, enabling state-level policy analysis. MA3T uses Microsoft Excel as its platform. The model's algorithms are run in Visual Basic Macros. MA3T uses a nested multinomial logit structure that predicts purchase probabilities given a large set of inputs, such as total cost of ownership (TCO) by vehicle type, fuel economy, daily mileage, and many other similar variables collected at the state-level. Additionally, certain inputs are disaggregated further to rural, urban, and suburban shares or values (e.g., charging availability, housing stock). MA3T's key outputs are vehicle sales, by year, for four vehicle categories (sedans, pickup trucks, crossover vehicles, and full-size SUVs) and four fuels/powertrains (battery-electric, plug-in hybrid electric, hydrogen fuel cell electric, and internal combustion engine gasoline vehicles). The model offers further detail in vehicle range and vehicle fuels which were not used in this study due to the focus of the research. The full model documentation and the model download is available on Oakridge National Laboratory's website.[10] Table 3 below describes the key inputs of the model.

[10] Lin, Z (2020). MA3T Model. https://teem.ornl.gov/assets/custom/pdf/ma3t_fact_sheet.pdf

Table 3. Summary of inputs to MA3T model.

Input Category	Inputs
Technology Inputs	Retail cost, fuel costs, maintenance cost, resale value, lifetime miles, fuel tank capacity, fuel economy, vehicle weight, cargo space, passenger capacity, towing capability, year technology is introduced to market.
Consumer Inputs	Housing stock, attitudes towards new technology, breakdown of urban type, value of range anxiety, type of driver, daily miles distribution for state, charging time, city driving share, parking value, high occupancy vehicle (HOV) lane access value, charging availability by charger type, refueling detour time.
Policy Inputs	Federal, state fiscal and non-fiscal policies.
Infrastructure Inputs	Fuel and infrastructure costs and availability.

4.1.2 Updates to Model

By and large, default values were used when generating Reference Case projections of vehicle sales. Three main updates were made to retail costs of vehicles, the vehicles available on the market, and the year vehicles are introduced to the market. These updates are described below. For all other inputs in MA3T, MA3T's default settings were used. These inputs can be reviewed on the MA3T homepage.[11]

Vehicle retail costs are key drivers of MA3T's estimated vehicle sales. MA3T default vehicle retail costs are estimated using the *Autonomie* vehicle simulator maintained by Argonne National Laboratory.[12] These default values have BEVs with a 100-mile range reaching retail cost parity with the same size class of internal combustion engine vehicles (ICEVs) (e.g., sedan) in 2035. BEVs with 200- and 300-mile range do not reach cost parity with ICEVs by 2050. Similarly, PHEVs of 10-mile, 20-mile, and 40-mile all-electric range never reach retail cost parity with the comparable ICEV vehicle before 2050. These cost assumptions are considerably more conservative than other recent estimates. For example, in 2019, the International Council for Clean Transportation (ICCT) reviewed a wide range of studies on cost parity between EVs and ICEVs. Depending on the vehicle category and the all-electric range, the authors estimate parity of retail cost to occur between 2023-2028.[13]

Vehicle retail EV costs were updated to be more conservative than the ICCT study but more optimistic than the MA3T default settings. These assumptions appear to align with the current market in Massachusetts: for the 16 BEV and 9 PHEV models available for incentive in Massachusetts' MOR-EV program,[14] the average MSRP across models (i.e., without state or federal incentives) is $35,187. For comparison, Kelly Blue Book data suggests that the average Manufacturer's Suggested Retail Price (MSRP) of internal combustion engine vehicles (ICEVs) vehicles ranges from $16,898 for a sub-compact to $117,700 for high performance cars. Figure 8 shows the retail cost assumptions for six types of sedans. Note that vehicle retail cost curves for other vehicle types (e.g., pickup truck, SUV) are not shown but follow similar trajectories, adjusted slightly based on

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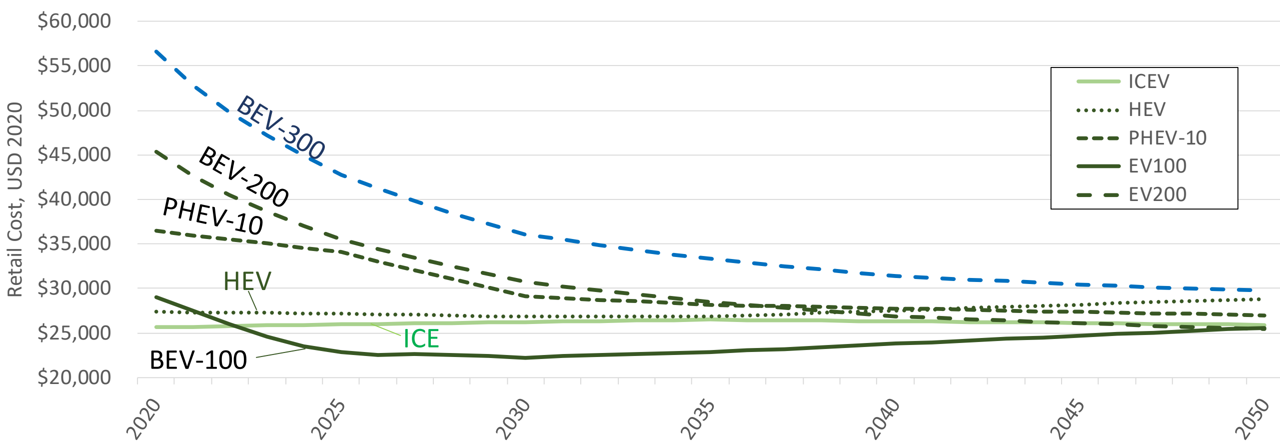
[11] Ibid.
[12] Argonne National Laboratory (2020). The Autonomie Model. https://www.autonomie.net/
[13] Lutsey, N. & Nicholas, M. (2019). Update on Electric Vehicle Costs in the United States Through 2030. International Council on Clean Transportation. https://theicct.org/publications/update-US-2030-electric-vehicle-cost
[14] Commonwealth of Massachusetts (2020). MOR-EV Eligible Vehicles. https://mor-ev.org/eligible-vehicles

the relative vehicle size.

The vehicle availability was also updated in MA3T, which has the ability to model 300 different vehicle-fuel combinations, including five types of body types and 60 different fuel and powertrain types. Because the main interest of this study was on exploring electric vehicle policies, we omitted all vehicle-fuel combinations except EVs, ICEVs, and hybrid electric vehicles.

Figure 8. Cost assumptions in MA3T model for sedans. Other vehicle categories not shown for brevity.



The final update to the MA3T model default assumptions concerned the year a vehicle type is introduced into the market. All LDV categories that do not currently have a model available on the market were assumed to become available in 2025, an assumption supported by announcements made by various automakers.[15] The following are vehicle types introduced in 2025: Crossover PHEV-40, pickup PHEV-10, pickup PHEV-20, pickup PHEV-40, pickup BEV-200, pickup BEV-300, SUV PHEV-40, and SUV BEV-300.

For the policy analysis described in Chapter 5, MA3T inputs were updated to reflect various policies, such as vehicle purchase incentives, EV supply equipment (EVSE) installation, and a carbon tax. These inputs modify the choice set presented to simulated vehicle buyers through the underlying logistic curves in MA3T.

4.2 EERPAT

4.2.1 Model Overview

The EERPAT model is a policy impact tool that estimates vehicle sales, vehicle stock, emissions, VMT, and energy use for household vehicles, commercial vehicles, trucks, and transit (both bus and rail) for any year to 2050. Cadmus Team member, Resources Systems Group (RSG), enhanced a version of EERPAT that was previously calibrated in 2015 for conditions in Massachusetts by the Massachusetts Department of Transportation.[16] The EERPAT model has been used in other jurisdictions to evaluate transportation investment and policy strategies – such as increased transit service, pricing, parking management, land use

[15] See, for example, McKinsey (2020) The road ahead for e-mobility. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-road-ahead-for-e-mobility

[16] Cambridge Systematics (2017). Application of the EERPAT Greenhouse Gas Analysis Tool in Massachusetts. https://www.mass.gov/doc/eerpat-report/download

strategies, etc. – to assess how different combinations of investment and policy actions impact travel behavior. EERPAT's role in this project was to (1) estimate VMT and mode shift impacts from policies; and (2) estimate policy impacts to medium- and heavy-duty vehicles, and rail. EERPAT runs at the county level, or Regional Planning Organization (RPO) level for Massachusetts. It is based on a system of disaggregate household-level models which function together to creates synthetic households and estimates changes in travel and vehicles based on household attributes. The sub-model linkages allow EERPAT to account for complex interactions between policies.

At a high level, EERPAT is considered a strategic model, a class of models which are defined as "disaggregate demand/aggregate supply" travel demand models. They combine the rich demographic and socioeconomic detail of simulated households with aggregate treatments of travel. By creating a synthetic set of individual households – each associated with a household income, vehicle ownership, and other characteristics – strategic models can examine equity effects and the impacts of fuel prices and other pricing policies, changes in population demographics and employment, and other factors on mode choice and travel behavior.

Figure 9. Conceptual diagram of EERPAT structure.

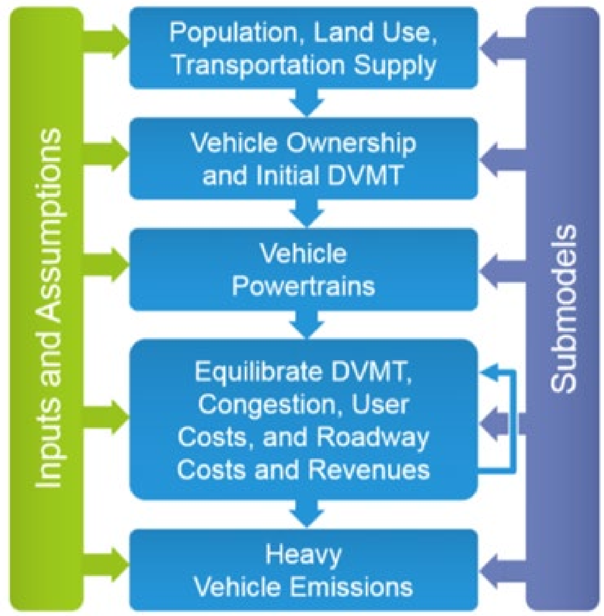


Figure 9 shows a conceptual overview of the model flow.[17] A more detailed description of all modeling decisions used to develop the model is available in the Massachusetts Department of Transportation EERPAT methodology document.[18] The blue boxes in the middle identify the major steps in the model execution process, which are carried out by different sub-models.

EERPAT involves many inputs and outputs. Key inputs-- grouped by changes in demographics and land use, policy and pricing, and changes in supply--are shown in Table 4. Users can evaluate the effects of specific policies or investment decisions by making changes to input files and reviewing the impacts on model outputs. Some of the data inputs are developed for the entire Commonwealth and others are developed at smaller, more localized geography levels (e.g., county or metropolitan statistical area).

[17] Ibid.

[18] Cambridge Systematics (2017). Application of the EERPAT Greenhouse Gas Analysis Tool in Massachusetts. https://www.mass.gov/doc/eerpat-report/download

Table 4. Key EERPAT inputs.

Changes in Demographics and Land Use	Local Policy Actions and Pricing	Changes in Transportation Supply
• Changes in population & demographics • Changes in average income per capita • Changes in employment • Changes in proportion of houses in mixed-use areas • Residential & workplace EV charging infrastructure	• Parking pricing programs • Demand management policies • Suitability for active transportation • Diversion of single occupancy vehicle trips by bikes, e-scooters, or other personal modes • Road cost recovery • Congestion fees • Pay-as-you-go insurance & other road fees • VMT fee	• Changes in freeway & arterial lane miles • Powertrain proportions for light-duty, transit & medium/heavy-duty vehicles (by ICEV, HEV & PEV) • Amount of regional transit service • Intelligent transportation system strategies for freeways & arterials

Primary outputs for EERPAT include program costs, household travel, fuel and power consumption, and GHG emissions calculations. Table 5 shows one possible set of output metrics from EERPAT that can be summarized at the state level.

Table 5. EERPAT output metrics.

	Outputs
Mobility	Daily VMT per capita
	Daily walk trips per capita
	Daily bike trips per capita
Economy	Annual household parking costs
	Annual household vehicle operating cost (fuel, taxes, parking)
	Annual household ownership costs (depreciation, vehicle maintenance, tires, finance charge, insurance, registration)
Land Use	Residents living in mixed-use areas
	Housing types (single family, multi-family)
Environmental	Annual GHG emissions per capita
	Household vehicle GHG per mile
	Commercial vehicle GHG per mile
	Transit vehicle GHG per mile
Energy	Annual all vehicle fuel consumption per capita (gallons)
	Average all vehicle fuel efficiency (net miles per gallon)

4.2.2 Updates to Model

To create the Reference Case conditions, Cadmus revised the version of EERPAT created by Cambridge Systematics,[19] by updating the base year inputs from 2013 to 2015 for four key model drivers:

- Median household income by county;[20]
- Vehicle counts for automobiles, trailers, light-trucks, heavy-trucks, motorcycles, and other;[21]

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[19] Cambridge Systematics (2017). Application of the EERPAT Greenhouse Gas Analysis Tool in Massachusetts. https://www.mass.gov/doc/eerpat-report/download
[20] US Census (2015). American Community Survey. https://www.census.gov/programs-surveys/acs
[21] Massachusetts RMV dataset provided to Cadmus by EEA.

- Vehicle-miles traveled (VMT) by RPO;[22]
- Motor fuel sales.[23]

Following model calibration by RSG, Cadmus used the updated EERPAT model to run sensitivities as described in subsequent chapters.

4.3 Transportation Sector Accounting Tool

The Transportation Sector Accounting Tool (TSAT) is an accounting spreadsheet that estimates, tracks, and integrates outputs from MA3T, EERPAT, as well as exogenous assumptions developed in coordination with EEA. TSAT allows users to understand the evolution of all subsectors of Massachusetts' transportation sector between today and 2050, across emissions, costs, energy use, number and type of EV chargers, electricity demand, and travel demand. TSAT was developed by Cadmus specifically to address questions related to this study and the transportation sector.

TSAT serves three main functions:

1. To characterize subsectors not modeled in the diffusion model or EERPAT, such as aviation and marine, thereby ensuring a complete perspective of the transportation sector;
2. To harmonize outputs of MA3T and EERPAT model (vehicle types, geography, timeframe, etc.);
3. To provide a simple, flexible tool to make assumptions and calculations as new analysis needs develop.

TSAT is based loosely on Argonne National Laboratory's VISION Tool, which provides similar functionality for projections at the national-level. The State of California similarly has a state-level "California VISION" tool the California Air Resources Board uses for deep decarbonization planning in the transportation sector. TSAT includes a series of tabs within a single Excel file. Table 6 summarizes the vehicle-fuel combinations represented in each of the sub-sectors.

Table 6. Summary of vehicles and fuels included in TSAT.

Subsector	Vehicle Categories	Fuels/Powertrains
Light-duty	Passenger, pickup truck, sports utility vehicle, van, crossover	Electricity, hydrogen, E10 gasoline, renewable gasoline
Medium/Heavy-Duty Vehicle Passenger	Transit bus, intercity bus, school bus, motor home	Electricity, hydrogen, renewable diesel, diesel, biodiesel, renewable natural gas, liquefied natural gas, compressed natural gas
Medium/Heavy-Duty Vehicle Freight	Short-haul single unit, short-haul combination unit, long-haul single unit, long-haul combination unit, refuse, light-commercial trucks	Electricity, hydrogen, renewable diesel, diesel
Aviation	<250 miles, 250-500 miles, 500-750 miles, 750-1000 miles, 1000-1250, 1250-1500, >1500	Electricity, jet fuel, sustainable aviation fuel
Rail	Passenger, freight	Electricity, diesel
Marine	Passenger, freight	Electricity, diesel

[22] Data provide by the Massachusetts Department of Transportation.
[23] FHWA (2015). Highway Statistics, Table MF-2. https://www.fhwa.dot.gov/policyinformation/statistics/2015/mf2.cfm

TSAT includes a wide variety of inputs and outputs. The total number of vehicles, VMT, and costs of travel are a key input to TSAT from the output of EERPAT. The share of BEVs and PHEVs are key inputs to TSAT from the output of the MA3T model. All other inputs are exogenously assumed by Cadmus in close coordination with EEA. For example, growth rates of service demand, fuel consumption, and costs will be assumed based on literature values and expert stakeholder input.

TSAT is a model that allows asking "What if" questions related to technology adoption. For example, TSAT is the appropriate tool to answer the question: what if electric bus adoption accelerates to twice the current rate? What are impacts on emissions and energy use in 2040? In contrast, policy questions related to a specific type of policy (e.g., a $5,000 vehicle subsidy) must be addressed in either EERPAT or the MA3T model. The full set of inputs for the TSAT tool are shown in Table 7. As noted above, outputs can be any combination of energy, emissions, costs.

Table 7. Summary of key inputs for TSAT, by source.

Input	Subsectors	Source of Input
Average freight ton-mile, by mode	MDHD vehicle, rail, aviation	Bureau of Transportation Statistics (BTS)
BEV and PHEV new vehicle sales share, by county	LDV	Diffusion Model output
Breakdown of air travel, by distance	Air	Federal Aviation Administration statistics
Emissions factors	All	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model
Freight load (tons per vehicle)	MDHD vehicle	Literature or user assumption
Growth in pass-miles and ton-miles	Air, marine	User assumption
Life expectancy of vehicles	LDVs, MDHD vehicles	Transportation Energy Databook
Lifetime cost of chargers, by type, by county	LDV, MDHD vehicle	EVSE Accounting Tool
Lifetime miles	LDV, MDHD vehicle	Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool and user assumption
Number of chargers, by type, by county	LDV, MDHD vehicle	EVSE Accounting Tool
Passenger load (people per vehicle)	LDV	Literature or user assumption
Share of alternative fuels in MDHD vehicles, rail, marine, and air, by year	MDHD vehicles, rail, marine, and air	User assumptions
Total cost of ownership	LDV, MDHD vehicle	TCO modeling
Total cost of ownership	Air, marine, rail	Literature
Unit conversions	All	Standard conversion reference
Vehicle efficiency	All	AFLEET tool and literature
Vehicle efficiency improvements over time	All	User assumption
EERPAT outputs	LDV, MDHD vehicle, rail, walk, bike & e-scooter	EERPAT outputs
Hourly electric demand from EVs for a full year, by city and load zone	LDV, MDHD vehicle	EVSE Accounting Tool

4.4 Other Data

In addition to modeling, the Cadmus team used a variety of other data and tools, such as the EVI-Pro tool, Census data, American Housing Survey, 2017 National Household Travel Survey data, EVHub data, and academic literature.

4.5 Limitations of Model Framework

The reader should use caution when interpreting results from the above model framework. The following are key modeling limitations:

- **Market effects in MA3T model**. MA3T does not allow model users to measure the level of free-ridership inherent in EV incentives (i.e., the fraction of EV buyers who would have purchased the EV even in the absence of the incentive). Rather, the output from MA3T is a gross adoption rate, which includes both program-induced effects as well as free-riders. To understand the level of free-ridership (as well as other important market effects like spillover and market acceleration), a rigorous program evaluation is needed after implementation of the incentive.
- **Uncertainty in human vehicle purchase behavior.** While vehicle choice models such as MA3T are useful for comparing future sales trends under different policy/technology assumptions, their ability to predict vehicle purchase decisions is limited because humans are economically irrational actors who are impacted by peers.
- **Cost feedbacks.** As shown in Figure 7, total costs of ownership are exogenous inputs into both EERPAT and MA3T. In scenarios with high EV adoption in the future, the low relative operational cost of driving EVs compared to ICEs could lead to greater VMT, although this feedback is not explicitly modeled.
- **Ridehailing and vehicle automation.** Due to limitations to state-level models, ridehailing and vehicle automation were not modeled in the above framework. This is an area of growing interest to the Commonwealth and deserves further research to understand the extent of GHG emission impacts. For example, the Metropolitan Area Planning Council (MAPC) notes that ridehailing has grown significantly in the Commonwealth and resulted in a net increase of 100,000 metric tons of carbon dioxide equivalent in 2018. Ridehailing has also resulted in a loss of $23 million in revenue for the MBTA as travelers choose ridehailing over travel via public transit.[24] More research is needed to understand which ridehailing applications and routes are best suited for electrification. Automation poses a separate set of challenges. However, the impacts of automation are still unclear. Research has shown that automation could either halve emissions or double them, depending how several factors manifest in the future, such as energy intensity, travel demand, and fuel mix.
- **Mobility and accessibility**. The modeling framework focuses on GHG mitigation strategies using vehicles, fuels, travel demand, and mode shift, but does not address broader objectives, such as mobility and access.

[24] Metropolitan Area Planning Council (2019). The Growing Carbon Footprint of Ride-Hailing in Massachusetts. http://www.mapc.org/wp-content/uploads/2019/07/Growing-Carbon-Footprint-of-Ride-hailing-in-MA.pdf

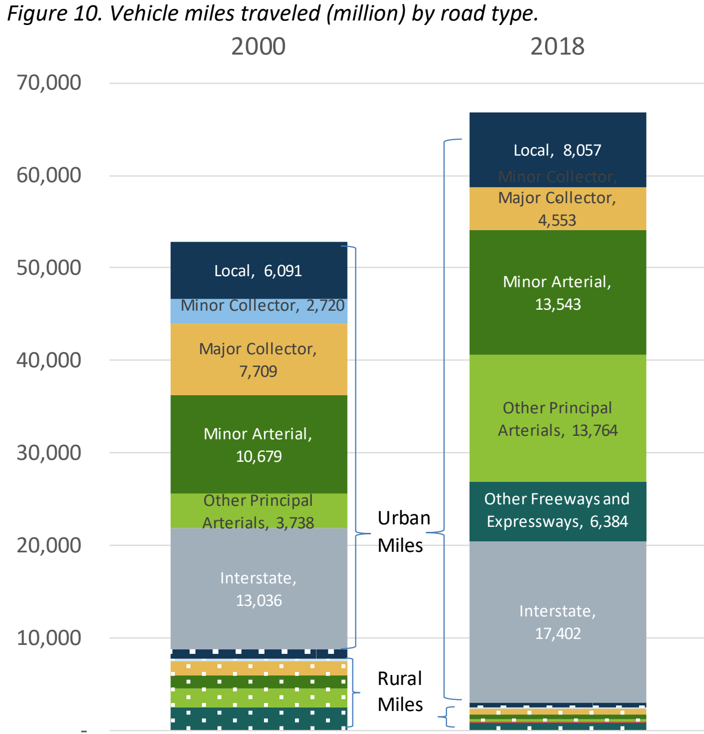
5 Light-Duty Sub-Sector

This Chapter describes the analysis of the Commonwealth's LDV sector. Of all sub-sectors or fuels in this report, the most detailed analysis is provided for light-duty electric vehicles below. This is due to the sub-sector's outsized contribution to the Commonwealth's transportation emissions, the relative market maturity of zero-emission vehicle technologies in the light-duty sub-sector, and the potential for the high-volume light-duty sub-sector to catalyze cost reductions for other, more difficult to decarbonize, lower-volume sub-sectors.

5.1 Trends in Light-Duty Sub-Sector

Massachusetts' light-duty sub-sector has about five million passenger cars and light-trucks and 156,000 motorcycles, and contributed 58% of Transportation Sector GHG emissions in 2017.25 Compared to the national average, Massachusetts' LDV sub-sector includes a higher fraction of passenger cars and fewer annual miles per capita.26 Together, this means that passenger cars account for 78% of vehicle-miles travelled in Massachusetts compared to the national average of 71%.[27] Total travel demand is increasing in Massachusetts. Figure 10 shows the total VMT in millions of miles for all on-road vehicle types for 2000 and 2018.[28] Urban VMT has grown while rural VMT has declined. Urban roadways are defined as areas with greater than 5,000 people.[29] Note that rural miles account for a relatively small fraction of total VMT, particularly in 2018. Most of the Commonwealth's population, vehicles, and travel occur in the Boston Metropolitan area, a major reason why per capita VMT in Massachusetts is lower than the national average and why the mode shift and densification strategies discussed in section 5.5 do not result in significant VMT reductions. 70% of MA's population lives in cities or towns of at least 1,000 residents per square mile, and at an average of 850 people per square mile Massachusetts is the third-most densely populated state in the U.S. (behind New Jersey and Rhode Island). Moreover, of the fifty states, Massachusetts

Figure 10. Vehicle miles traveled (million) by road type.



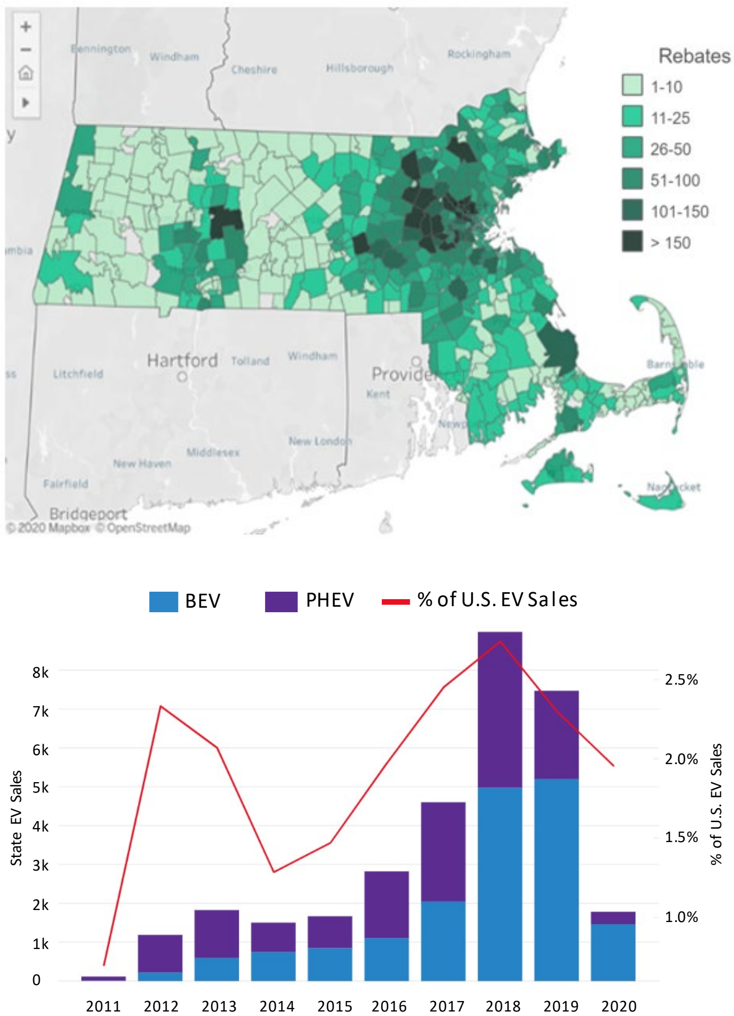
[25] FHWA (2018). Highway Statistics, Table VM-1. https://www.fhwa.dot.gov/policyinformation/statistics/2018/mv1.cfm
[26] FHWA (2018). Highway Statistics, Table VM-4.
[27] Ibid.
[28] FHWA (2000, 2017) Highway Statistics. Table VM-4.
[29] FHWA (2020). Highway Functional Classifications. https://www.fhwa.dot.gov/planning/processes/statewide/related/highway_functional_classifications/section06.cfm

ranks 39th in average VMT per capita.[30] At more than 360 million unlinked trips, the Massachusetts Bay Transit Authority (MBTA) was the fourth-most utilized public transit agency in the United States in 2019, behind New York, Chicago, and Los Angeles.

5.1.1 Status of the EV Market in Massachusetts

As of July 2020, Massachusetts had an estimated 31,962 EV registrations, 54% of which were BEVs and 46% of which were PHEVs.[31] In 2019, EVs accounted for over 2% of new LDV sales or 4.7 EVs per 1,000 people. As shown in Figure 11. (top), the highest number of EV rebates have been distributed in the state's most populous region, suburban Boston.[32] EV sales peaked in 2018, which coincided with the release of Tesla's Model 3 (Figure 11., bottom).

Figure 11. EV deployment by county as of August 2020 (top) and over time through August 2020 (bottom).



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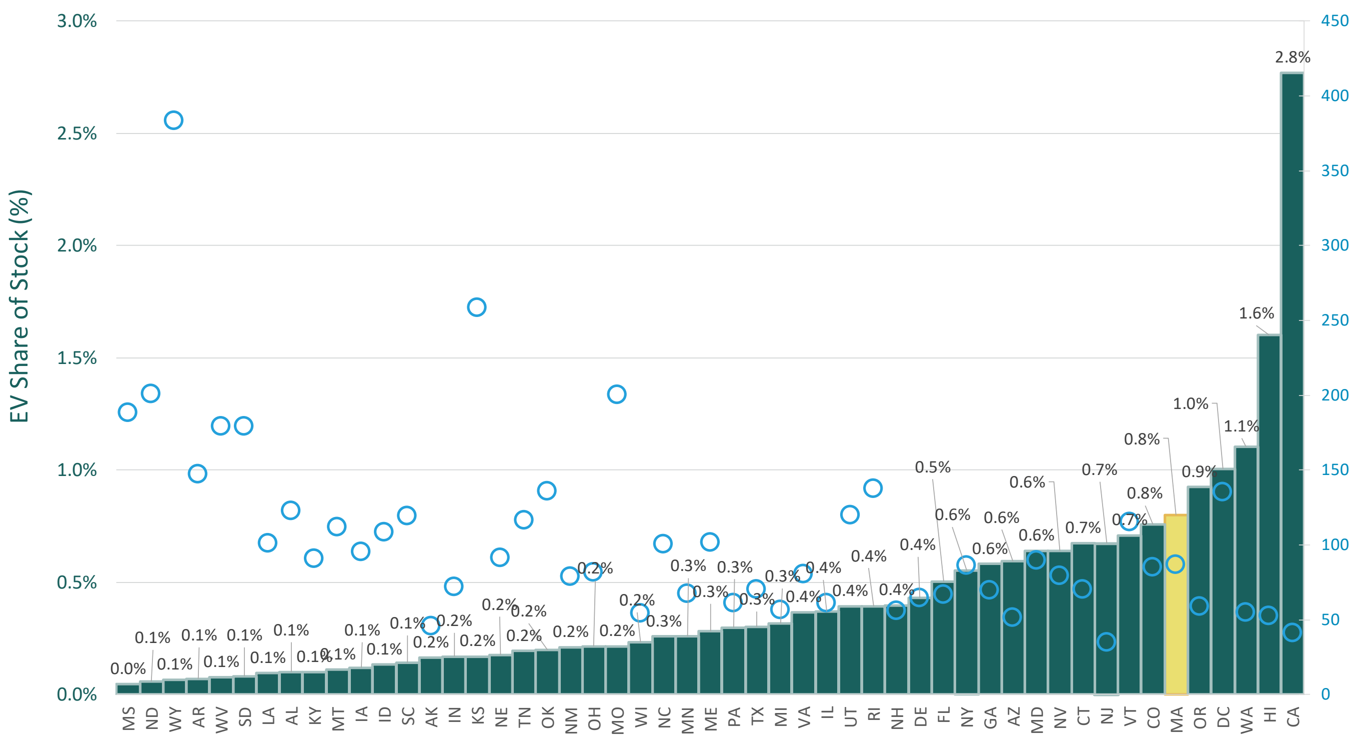
[30] U.S. DOT, FHWA (2018). Highway Statistics, Table VM-2. https://www.energy.gov/eere/vehicles/articles/fotw-1113-december-23-2019-average-annual-highway-vehicle-miles-traveled
[31] Atlas Public Policy (2020). EVHub. https://www.atlasevhub.com/ Note: Log-in requires subscription to site.
[32] Commonwealth of Massachusetts (2020) MOR-EV Rebate Statistics. https://mor-ev.org/

According to the Alternative Fuels Data Center,[33] there are 2,372 publicly available level 2 plugs available in Massachusetts, of which 4% are Tesla plugs that cannot be used by other brands of EVs. The DC fast charger market is characterized by three primary plug types—CCS, CHAdeMO, and Tesla. There are 322 fast charger plugs in Massachusetts, of which 61% are Tesla plugs.

Figure 12 provides a comparison between Massachusetts with other states in terms of EV and EV charger deployment. The bars in Figure 14 show the estimated share of LDV stock that are electric by state, while the blue circles show the ratio of publicly available charging plugs per 1,000 registered EVs. The key insight from Figure 12 is that Massachusetts has the 6th highest EV share of its vehicles stock (blue bars) and comparable (but slightly higher) levels of EV publicly available charging deployment as other states in the top 20 ranked states in EVs.[34]

Figure 12. EVs (bars) and plugs (circles) per registered vehicle, by state.



Accelerating these trends will require consideration of how consumers adopt new technologies. Rogers diffusion of innovations theory (Rogers theory) is useful to help visualize the dynamic when choice is the main driver of change.[35] As demonstrated in Figure 13, innovators are the first to adopt a new technology, followed by early adopters, early majority, late majority, and, finally, laggards. Each segment is defined by specific characteristics shown in Figure 13. As technology diffusion increases within a population, the adopters are increasingly price sensitive and resistant to change. Rogers (2003) emphasizes the importance of the first

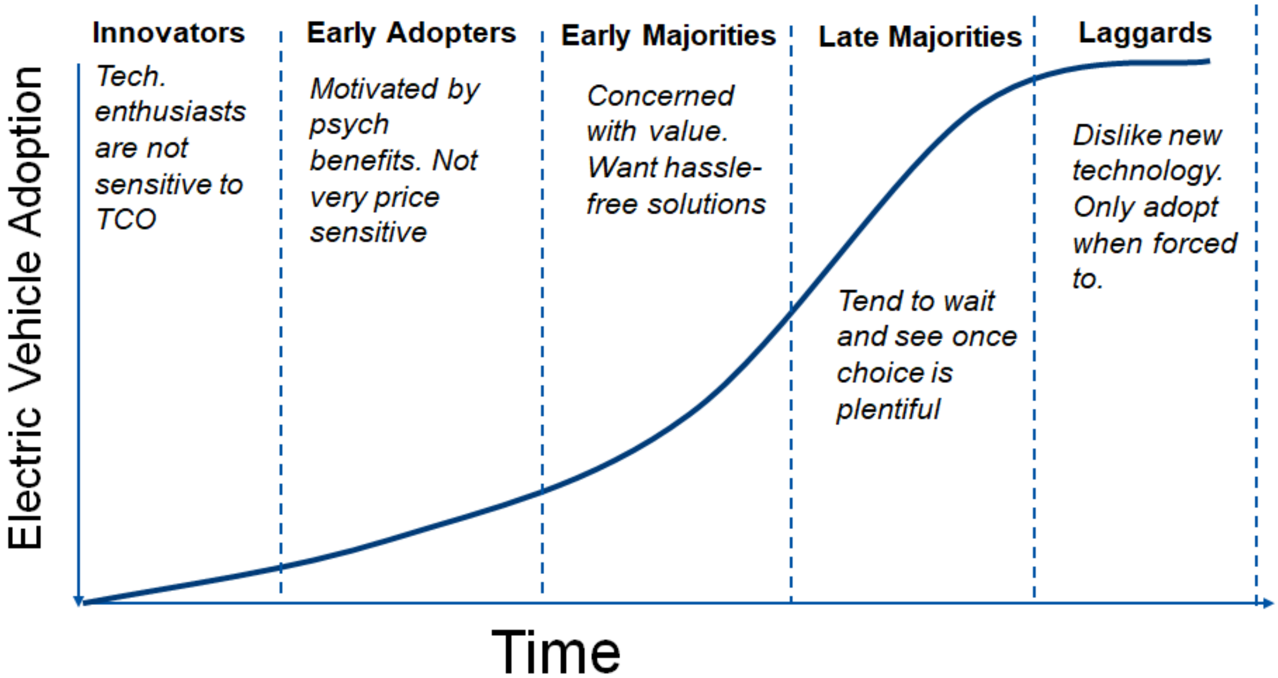
[33] United States Department of Energy (2020). EV Charging Station Locations. Alternative Fuel Data Center. https://afdc.energy.gov/fuels/electricity_locations.html#/analyze?region=US-MA&country=US&fuel=ELEC

[34] Cadmus analysis of Atlas Public Policy (2020) EVHub, https://www.atlasevhub.com/

[35] Rogers, Everett M., 2003. Diffusion of Innovations, 5th ed. Free Press, New York.

adopters of a new innovation. If the early adopters are satisfied with the product it will positively influence the rate of subsequent adoption. Rogers' conceptual framework is used in much of the LDV analysis below.

Figure 13. Technology diffusion curve over time, showing distinct segments of adopters and their general characteristics. Adapted from Rogers (1990).



5.1.2 Results of Electric Vehicle Analysis

The modeling of electric vehicles and EVSE includes a wide range of topics, including BEV incentives, PHEV incentives, EVSE incentives, and EV load impacts. Each is described in the sections below.

5.1.2.1 Reference Case

Projections for a Reference Case are shown in Figure 14 below. The top row shows all LDV sales and stock by vehicle technology while the bottom row shows LDV sales and stock by size class. The reference case for EV adoption is neither strictly a "no policy" nor a "policy" case; since the vehicle market is global, policies put in place throughout the world have had an influence on the market. The Reference Case used for this analysis explicitly includes the federal EV tax credit,[36] the current ZEV mandate (ending in 2025), and the federal Corporate Average Fuel Economy (CAFE) standards,[37] but does not include the current MOR-EV rebate.[38] The Reference Case also includes, indirectly, the currently observed and forecast reaction of the global auto industry to regulatory requirements around the world, particularly in Europe, responding to the need to decarbonize transportation systems. As described in Chapter 4.1.2, three updates to the default values for

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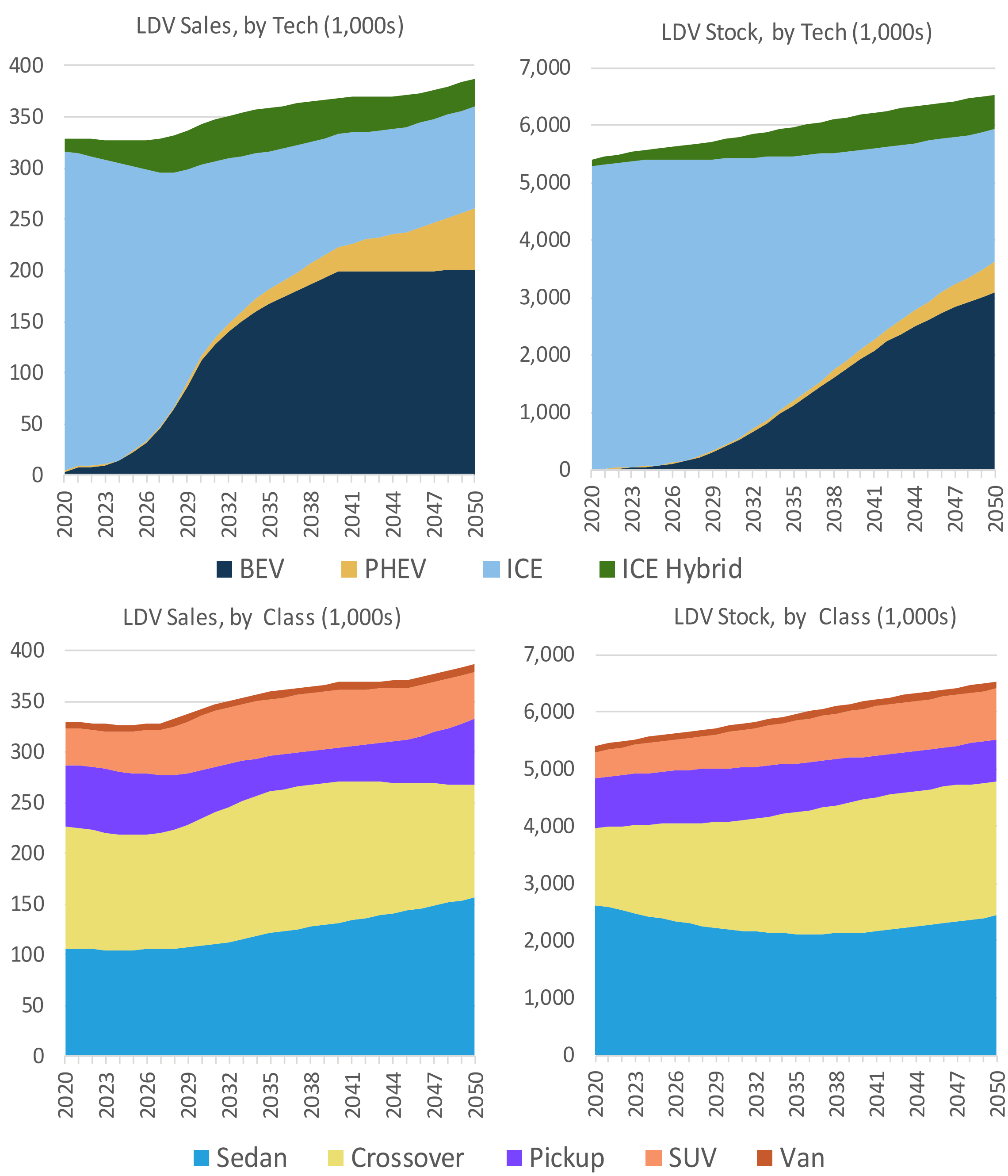
[36] MA3T phases out the federal EV tax credit after 200,000 EVs for each automaker.
[37] Fuel economy modeled based on the Obama-era standards. After 2025, fuel economy continues improving at similar rates of change for each vehicle category. See MA3T documentation for exact rate of change.
[38] MOR-EV rebate not modeled as part of the reference case because a central research question in this chapter is "what level of EV incentive is needed by the Commonwealth to drive EV sales to required levels of adoption?"

MA3T include updates on the vehicle retail costs, vehicle availability, and the year certain EV technologies enter the market. With the explicit and implicit policies build into the Reference Case, BEV and PHEV sales grow to become approximately 50% of all LDV sales by 2035. This result is consistent with projections from Bloomberg New Energy Finance who estimate a 52% EV sales share in 2035. The mix of vehicle classes (e.g., sedans versus crossovers) is roughly constant over time with the largest increase in sedans. Total LDV population in the Commonwealth rises from about 5.5 million in 2020 to over 6.5 million by 2050. Reference Case values are lower in the companion report to this current study – the *Energy Pathways Report* – which uses U.S. Annual Energy Outlook 2019 assumptions in the reference case for consumer adoption.

Figure 14. Reference Case projections for LDVs by vehicle technology (top two graphs) and by size class (bottom two graphs). Figures show both vehicle sales and vehicle stock.



It is worth noting that absent direct policy action like that announced recently by California,[39] or similar federal requirements on auto manufacturers, modeled sales of BEVs plateau around 2040 based on theoretical vehicle class-specific, policy-unconstrained consumer choice preferences embedded in the MA3T model, particularly surrounding vehicle size alongside the relatively slower emergence of cost-competitive larger electric vehicles. However, recent announcements from a variety of light truck manufacturers, in conjunction with state policies in progress,[40] suggest that battery electric vehicles may become available for these classes more quickly than MA3T would otherwise anticipate.

5.1.2.2 BEV Incentives

This section describes MA3T modeling of financial incentives aimed at increasing BEV adoption in Massachusetts. Based on the *Energy Pathways Report*, the Commonwealth should target about one million EVs on the road by 2030 to achieve neat-term emissions reduction goals and be on pace for a fully decarbonized LDV fleet by 2050. As indicated in Figure 14, without additional policies or incentives, Massachusetts would not be expected to reach that level of deployment until 2035 at the earliest.

Table 8 summarizes the various vehicle incentive scenarios run in MA3T, including varying levels of carbon taxes and vehicle purchase rebates, all-else-equal, at the time of vehicle purchase. Financial incentives were the focus of this analysis because of the usefulness of understanding the incremental impact of an additional dollar of subsidy on presumed customer purchasing preferences. However, financial incentives are just one policy instrument. In practice, similar levels of BEV adoption might be achieved through other means, such as binding vehicle standards or a combination of such standards together with a range of incentives. Below, the focus of the reader should be on the given price differential created through each policy examined.

Table 8. Scenarios run with MA3T on BEV-related policies.

Name	Description	Years Applied
Ref	Reference Case: no subsidy	n/a
$2K Subsidy	BEV subsidy of $2,000 per vehicle, no PHEV subsidy	2025-2050
$4K Subsidy	BEV subsidy of $4,000 per vehicle, no PHEV subsidy	2025-2050
$8K Subsidy	BEV subsidy of $8,000 per vehicle, no PHEV subsidy	2025-2050
$20 ton Carbon Tax	$20 per ton CO_2 tax applied starting in 2025	2025-2050
$100 ton Carbon Tax	$100 per ton CO_2 tax applied starting in 2025	2025-2050
Electric vehicle supply equipment & $10 - $200 CO_2	Carbon tax, gradually increasing from $10/ton to $200/ton	2025-2050

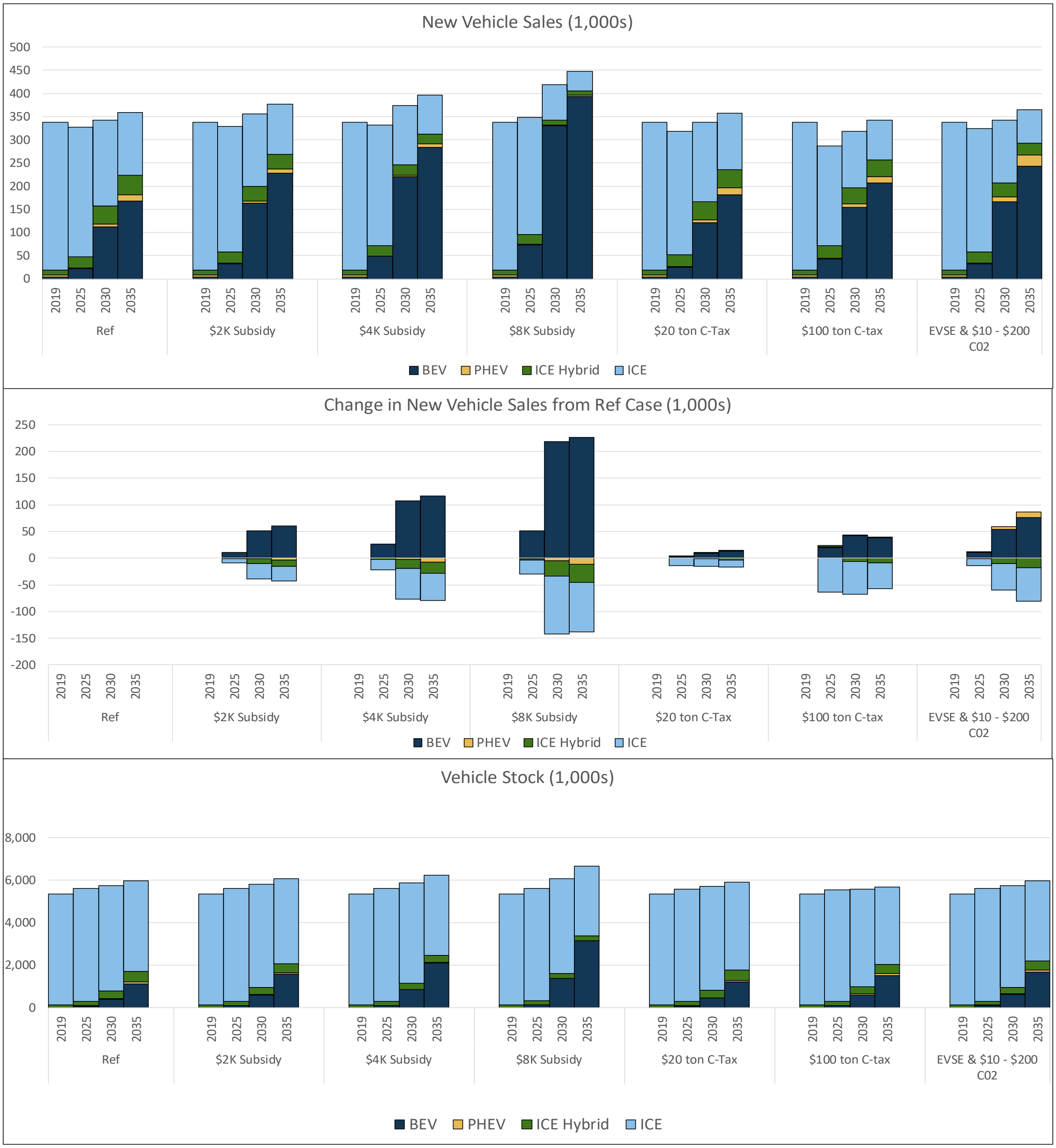
Figure 15 illustrates the BEV adoption under the seven scenarios in Table 8. Subsidies and carbon taxes results in greater BEV sales. Overall, the $8,000 per vehicle incentive results in much higher BEV sales by 2035 than any other policy case. Subsidies for BEVs result in net increases in total vehicle sales unlike carbon taxes, which results in a slight reduction in total sales. The $4,000 per vehicle subsidy achieves a BEV stock of just under one million in 2030. The $8,000 per vehicle incentive achieves a BEV stock of slightly over one million in 2030 and close to 100% electrification of new vehicle sales by 2035. Yet, even in this scenario BEVs only account for

[39] California's Executive Order N-79-20

[40] Szymkowski, CNET (2020). Hummer EV to Tesla Cybertruck and more: Every electric pickup truck coming https://www.cnet.com/roadshow/news/hummer-ev-tesla-cybertruck-rivian-nikola-electric-pickup-truck-coming/

roughly 50% of the total vehicle stock in 2035 (Figure 15, bottom). A carbon tax of approximately $100 per ton (in real dollars) applied from 2025 to 2050 results in roughly similar levels of BEV deployment as a $2,000 per vehicle subsidy and fewer total vehicle sales than BEV subsidies. In this analysis, no scenarios were developed that explored both carbon tax and vehicle purchase rebates; however those combinations could be an area studied in future policy analysis. Note that a $100 per ton carbon tax would likely have impacts on the Transportation Sector beyond the choices of vehicle technology illustrated in Figure 15, such as mode choice and VMT. These impacts were not explicitly modeled in this section.

Figure 15. Effects of incentives and carbon pricing on BEV adoption in Massachusetts. Top panel gives new vehicle sales. Middle panel shows change in new vehicle sales. Bottom panel gives vehicle stock. Source: Cadmus analysis using MA3T model.



Subsidies are a straightforward instrument for changing the economics of vehicle purchase decisions and increasing the number of new EVs sold annually. However, a potential downside of a vehicle purchase subsidy flows from the assumption that a subset of subsidy recipients would have purchased the BEV in the absence of the subsidy. Thus, the cost per *additional* BEV added to the road, above the Reference Case, is higher than the value of the subsidy.

Table 9 summarizes the impact of three subsidies – $2,000, $4,000, and $8,000 per BEV – on BEV annual sales for the years 2030, 2040, and 2050.[41] As shown, without a subsidy, total annual BEV sales are 112,000, 199,000, and 201,000 for the three time periods, respectively. With a $2,000 per BEV subsidy, annual BEV sales rise to 164,000, 272,000, and 291,000, respectively. This means the additional BEVs on the road due to the subsidy are 52,000, 73,000, 90,000, respectively. As shown in the far-right column, the $2,000 per BEV subsidy equates to a $6,000-$7,000 subsidy per additional BEV. As the subsidy value increases to $8,000 per BEV, the real cost per additional BEV also increases to as high as $13,797 per BEV.

Understanding the marginal cost of each additional BEV is useful because it can be compared to other EV incentive programs (including targeted subsidies) that more directly incentivize undecided vehicle buyers. Together, calculations in Table 9 illustrate the diminishing returns on undifferentiated purchase price subsidies: i.e., every additional dollar spent to subsidize EV adoption results in slightly fewer EVs per dollar of incentive (center column) and a higher cost per additional BEV (far right column). These diminishing returns are a result of moving up the theoretical Rogers' diffusion curve shown in Figure 13, towards consumers who are assumed to be less willing to adopt an EV and towards greater fractions of large vehicles (e.g., pickup trucks and sports utility vehicles), which are currently lagging in manufacturers' electrified model offerings.

Table 9. Analysis of total subsidy size and cost per additional BEV sale.

Year	Scenario	Total Annual BEV Sales (1,000s)	BEV Sales Share of Total LDV Sales (%)	Additional BEV Sales Above Ref Case (1,000s)	Annual Subsidy Cost ($1,000s)[1]	Cost per Additional BEV Sale ($)[2]
2030	Reference	112	33%	0	$0	$0
	$2K Subsidy	164	46%	52	$328,000	$6,308
	$4K Subsidy	220	59%	108	$880,000	$8,148
	$8K Subsidy	330	79%	218	$2,640,000	$12,110
2040	Reference	199	54%	0	$0	$0
	$2K Subsidy	272	69%	73	$544,000	$7,452
	$4K Subsidy	330	79%	132	$1,320,000	$10,000
	$8K Subsidy	439	92%	240	$3,512,000	$14,633
2050	Reference	201	52%	0	$0	$0
	$2K Subsidy	291	69%	90	$582,000	$6,467
	$4K Subsidy	358	81%	157	$1,432,000	$9,121
	$8K Subsidy	476	94%	276	$3,808,000	$13,797

[1]Estimated by multiplying BEV sales by incentive level.

[2]Estimated by dividing annual subsidy cost by the additional BEV sales above Ref Case (divide second from right column by third to right column).

[41] Incentives could also be tiered by income level, better matching the need with the incentive level.

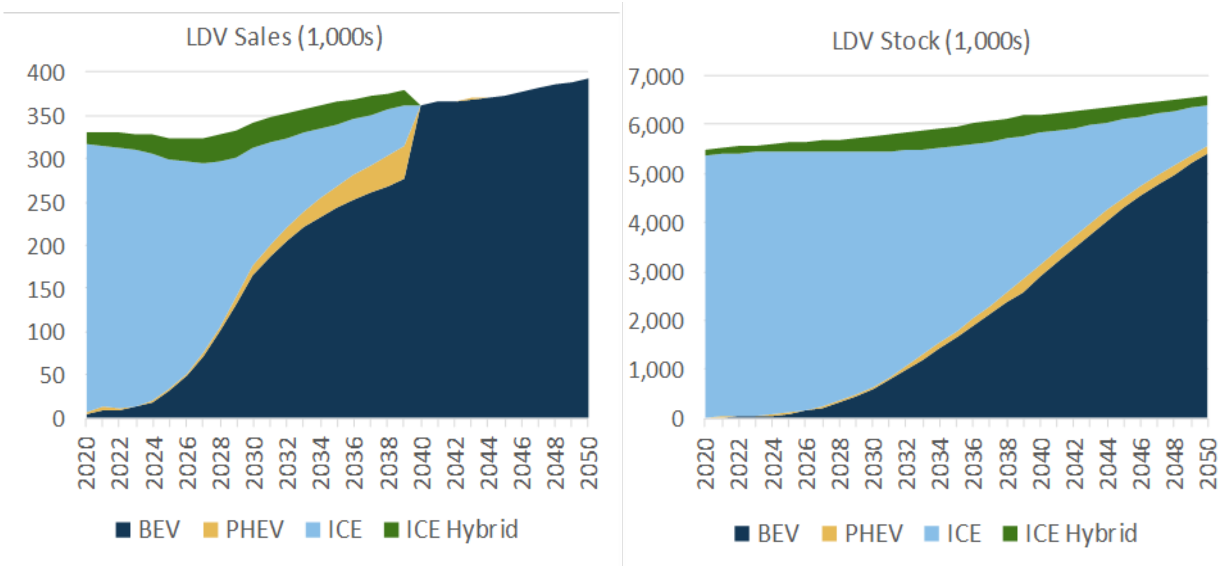
Given the large total annual funding needed to maintain subsidies, as shown in the second from right column of Table 9, it is unlikely that the Commonwealth would be able to continue funding incentives indefinitely. (It is also not likely that indefinite subsidies would be needed given policy actions aimed at re-incentivizing auto manufacturers, see section 5.2.2.3 below.) However, research from Jenn, et al. (2020) indicate that incentives become increasingly important over time because the characteristics of the average BEV buyer shifts with greater BEV penetration – from less price sensitive to more price sensitive until cost parity is achieved.[42] This trend points to a necessity of a sustainable funding mechanism in the future and/or a regulatory mechanism that forces automakers to internalize the risk of higher prices.

5.1.2.3 ZEV Standard

The proposed Advanced Clean Cars II regulation, led by the California Air Resources Board (which would be mirrored in Massachusetts under state law) would require increasing penetration of BEVs and FCEVs, leaving to an eventual phase out of sales of new ICEVs by 2035. More than two dozen global jurisdictions have announced some sort of ICEV phase out, either in terms of sales or for specific areas (e.g., "green zones").[43, 44] Such national and regional bans tend to include diesel and gasoline vehicles, but vary as to whether they also apply to hybrid electric vehicles and medium/heavy-duty vehicles.[45]

An ICEV phase-out can be modeled in several ways. In the analysis below, an ICEV phase-out scenario was implemented in MA3T using a CO_2 tax that ramps up from $10 per ton in 2025 to $200 per ton in 2050 with widespread publicly available charging access. Additionally, the scenario institutes a sales ban on ICEV vehicles (including PHEVs) in 2040. This ban was implemented in the model by adjusting the retail price of ICEVs to a prohibitive $1,000,000 per vehicle after 2039. The left panel of Figure 16 shows the sharp decline in ICEV sales in 2040 and the overall decline in total vehicle sales. As shown in the right panel of Figure 16, even with a

Figure 16. LDV sales and LDV stock under an ice phase-out occurring in 2040.



[42] Jenn, A. et al. (2020) An Examination of the Impact That Electric Vehicle Incentives Have on Consumer Purchase Decisions Over Time. https://escholarship.org/uc/item/0x28831g
[43] IEA (2020), Global EV Outlook 2020. https://www.iea.org/reports/global-ev-outlook-2020
[44] Plotz (2019), Designing Car Bans for Sustainable Transportation. https://www.nature.com/articles/s41893-019-0328-9
[45] Ibid.

virtual complete sales ban in 2040, ICEVs still account for 18% of all LDVs in 2050 because the median age of LDVs is greater than 10 years.

Early vehicle retirement programs ("cash for clunkers") provide one option for removing vehicles from the vehicle stock. While many of such programs have and continue to exist today, they are often focused on objectives other than GHG reduction – such as economic growth or criteria pollutants.[46] These programs can be designed to provide the largest incentive for removal of the highest polluting vehicles.

5.1.2.4 EVSE Incentives and Charging Availability

Expansion of charging is another strategy for increasing EV sales; independent of other incentives, increasing the deployment and availability of EV charging infrastructure would likely increase EV sales. This study explored this dynamic by examining six scenarios in which baseline charger availability was increased to determine the potential effect of such an increase on EV adoption rates.

In MA3T the term "charging availability" reflects the fraction of public, workplace, and residential parking spots that are within "a few minutes' walk" of charging. Seven scenarios, shown below in Table 10, were run to determine the impacts of charging incentives and charging availability on EV adoption. Following the Reference Case, the first four scenarios examine the impact of expanding availability of charging at the workplace, in public, or at home. For workplace and publicly available charging, this expansion implies expanding the fraction of parking spots that have close access to charging. For at-home charging availability, this expansion implies increasing the fraction of homes that have the necessary parking configuration and electricity access to facilitate at-home charging. This expansion of charging in these scenarios is assumed to be provided by an external entity, such as the government, utility, or charging station providers. The final two scenarios examine subsidies for at-home charging. In these scenarios, the cost of installing a charger and purchasing the equipment is reduced for residential chargers. These scenarios are similar to the Resi + 20% EVSE scenario (described in Table 10) but differ because they focus on cost reduction rather than access to charging.

Table 10. Summary of EVSE scenarios.

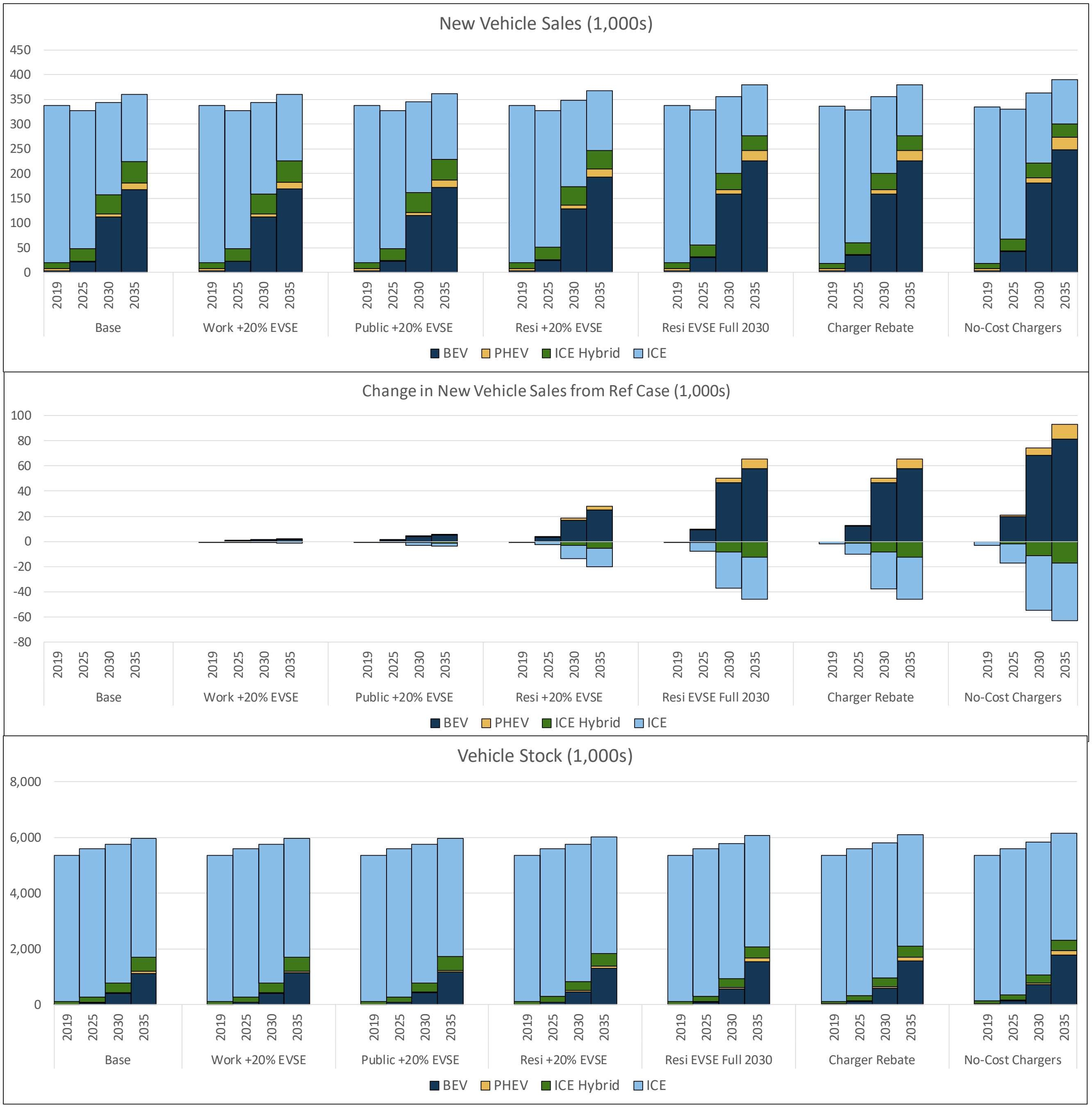
Scenario	Name	Description
1	Reference Case	No subsidy. Charging availability increases between 2020 and 2050 as shown below: • 2020: 34% in urban settings; 34% in suburban settings; 5% in rural settings. • 2050: 50% in urban and suburban settings in and 10% in rural settings
2	Work +20% EVSE	Workplace charging 20% higher than default
3	Public +20% EVSE	Publicly available charging 20% higher than default
4	Resi +20% EVSE	Residential charging 20% higher than default
5	Resi EVSE Full 2030	Residential charging availability reaches 100% by 2030
6	Charger Rebate	Subsidies for residential chargers. People with a garage or carport get $1,000 per charger subsidy. People in multi-unit dwelling get $7,000 per charger subsidy.
7	No-Cost Chargers	No cost residential EV chargers

Figure 17 shows the adoption of vehicles under the seven scenarios. Overall, the most aggressive EVSE scenarios have a smaller impact on EV sales than most vehicle subsidy and carbon tax scenarios. When

[46] Allan et al. (2009), Abating GHG Emissions with Cash for Clunker Programs. https://escholarship.org/uc/item/1h30m2r7

comparing the Reference Case with the scenarios 2-5, as indicated in Table 10, the results indicate that providing residential charging availability has greater impact on EV sales than workplace or public charging availability. Again, MA3T's definition of residential charging availability is the fraction of homes that have the ability to charge with an outlet and a parking spot. Charger incentives lead to greater EV uptake compared to the Reference Case. In the far-right scenario, paying for 100% of the installation and equipment costs of residential chargers (for detached and multi-unit homes) increases EV adoption by nearly 100,000 EVs per year by 2035 above the Reference Case.

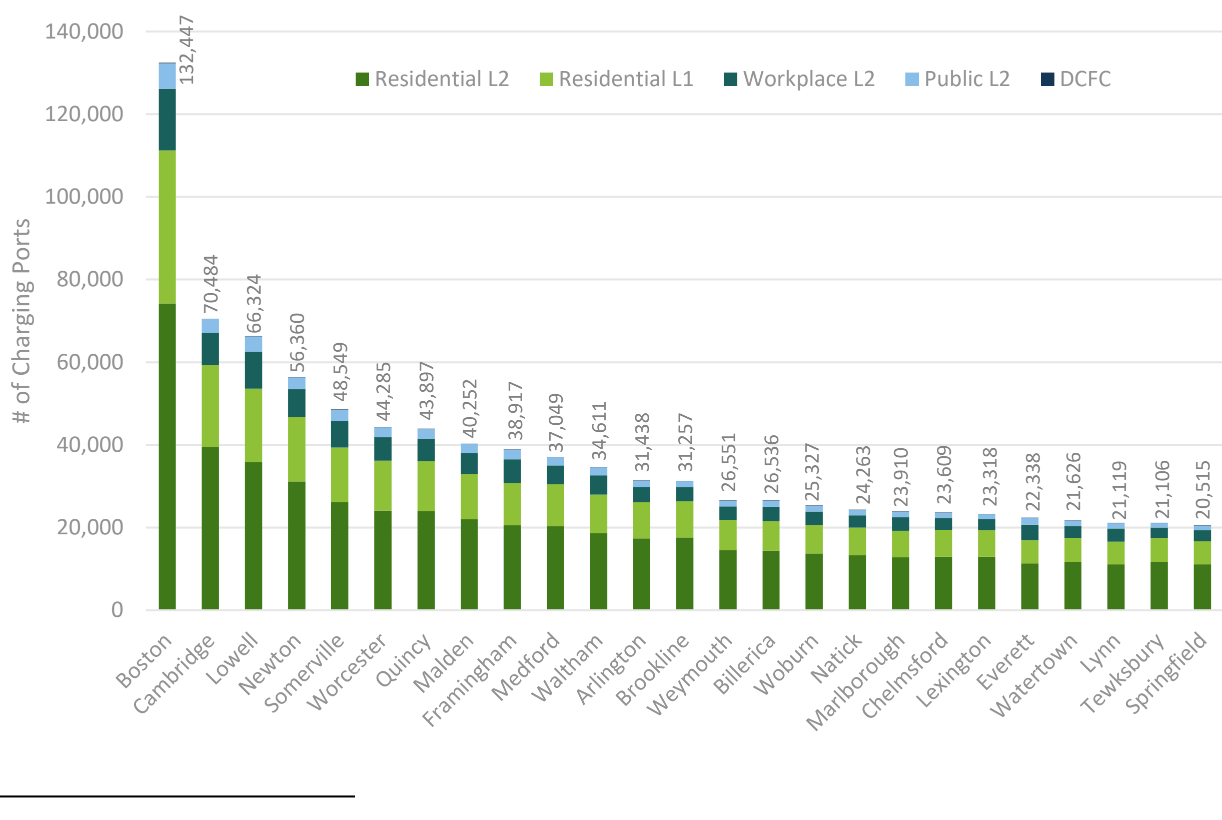
Figure 17. Effects of availability and cost of EVSE on vehicle adoption in Massachusetts. Top panel gives new vehicle sales. Middle panel shows change in new vehicle sales. Bottom panel gives vehicle stock. Source: Cadmus analysis using MA3T model.



This study's findings regarding the strong effect of residential charging availability is consistent with other research suggesting that—because residential charging is relatively convenient and inexpensive, and well-timed with typical use patterns (e.g., charging during overnight hours when most vehicles are not typically not operated)—more than 80% of current PHEV and EV charging typically happens at home.[47] As a result, the transition from ICE to EV may initially be easiest and cheapest for vehicle owners living in single-family or multi-family homes with access to garage or off-street parking.

Projections regarding EV charging habits out to 2050 are challenging as the EV market is still rapidly developing. However, using the best available information and tools today can play a useful role in providing an order of magnitude for charging needs and impacts. The EVSE Accounting Tool estimates the number of chargers, by charger type, using data from EVI-Pro Lite, which assumes a linear relationship between the number of EVs on the road and demand for different types of charging equipment. In addition, data from the US Census Bureau helps to break out the need for private and public charging ports by municipality. These breakdowns are based on a combination of total population, car ownership trends, and the percentage of households in each municipality that would have easy access to a home charger (e.g., owner-occupied, single-family home with off-street parking). Figure 18 shows the estimated number of chargers needed by type in 2050 in a fully electrified LDV Policy Case in the 25 Massachusetts municipalities that had the highest modeled demand for EVSE. Notably, the number of DC Fast Chargers is relatively small, with Boston demanding the highest number of DCFC ports (653) and with 15 towns in the Commonwealth not requiring a fast charger at all (not pictured in Figure 18). The majority of chargers are at homes, followed by workplace, and then publicly available.

Figure 18. Projected charging plugs needed in 2050 by town for Policy Case in 25 municipalities with highest modeled demand for EVSE



[47] U.S. Office of Energy Efficiency and Renewable Energy, Electric Vehicles: Charging at Home. https://www.energy.gov/eere/electricvehicles/charging-home

These trends are expected to evolve as the stock of EVs grows, and will be an important area to watch, but point to modest build out of publicly available charging to be a “no-regrets” action in the near term, particularly to provide EVSE access to those without off-street parking suitable for home-charging. Additional research however is needed as the Commonwealth works to design additional EVSE policies that equitably support the rapid and widespread deployment of EVs across the Commonwealth.

5.2 Hydrogen Fuel Cell Electric Vehicles

5.2.1 Status of Fuel Cells in Massachusetts

Hydrogen fuel cells are a technology that offer zero tailpipe emissions along with the potential for zero lifecycle emissions if the hydrogen is produced from renewable electricity. Unlike EVs, which can take many hours to recharge, FCEVs refuel in approximately five minutes and provide over 300 miles of range between refueling. The hydrogen fuel cell market continues to grow at a measured pace, with over 20,000 hydrogen fuel cell forklifts nationwide used for indoor material movement[48] and approximately 6,000 light-duty fuel cell electric vehicles (FCEVs).[49] As of August 2020, no FCEVs have received the MOR-EV rebate in Massachusetts. Four hydrogen fueling stations are ready for open retail in New England, in Mansfield and Braintree, MA, Providence, RI and Hartford, CT.

The vast majority of FCEVs are registered in California, which has actively invested in publicly available hydrogen stations and set targets for FCEV deployment. The red markers in Figure 19 indicate the growth of FCEVs in California.[50] The blue and orange bands show previous automaker projections. Uptake of FCEVs has undoubtedly lagged that of EVs. For example, in the first four years of BEV availability starting in 2010, 134,000 BEVs were sold nationwide.[51] In contrast, only 6,000 FCEVs have been sold in California. The California Air Resources Board assessed the pace of FCEV growth as insufficient to meet the state’s 2025 and 2030 FCEV deployment targets.[52]

Only three models of FCEVs are available in U.S. markets as of 2020: the Toyota Mirai, Hyundai Nexo, and Honda Clarity, with retail costs of around $60,000. FCEVs have potential for considerable cost reduction as manufacturing volumes rise and technological learning occurs.[53,54] The current hydrogen fuel price in California

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[48] US DOE (2018). Industry Deployed Fuel Cell Powered Lift Trucks. https://www.hydrogen.energy.gov/pdfs/18002_industry_deployed_fc_powered_lift_trucks.pdf

[49] CARB (2019). 2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development. https://ww2.arb.ca.gov/sites/default/files/2019-07/AB8_report_2019_Final.pdf

[50] CARB (2019). 2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development. https://ww2.arb.ca.gov/sites/default/files/2019-07/AB8_report_2019_Final.pdf

[51] Gohlke and Zhou (2020). Assessment of Light-duty Plug-in Electric Vehicles in the United States. https://publications.anl.gov/anlpubs/2020/06/158307.pdf

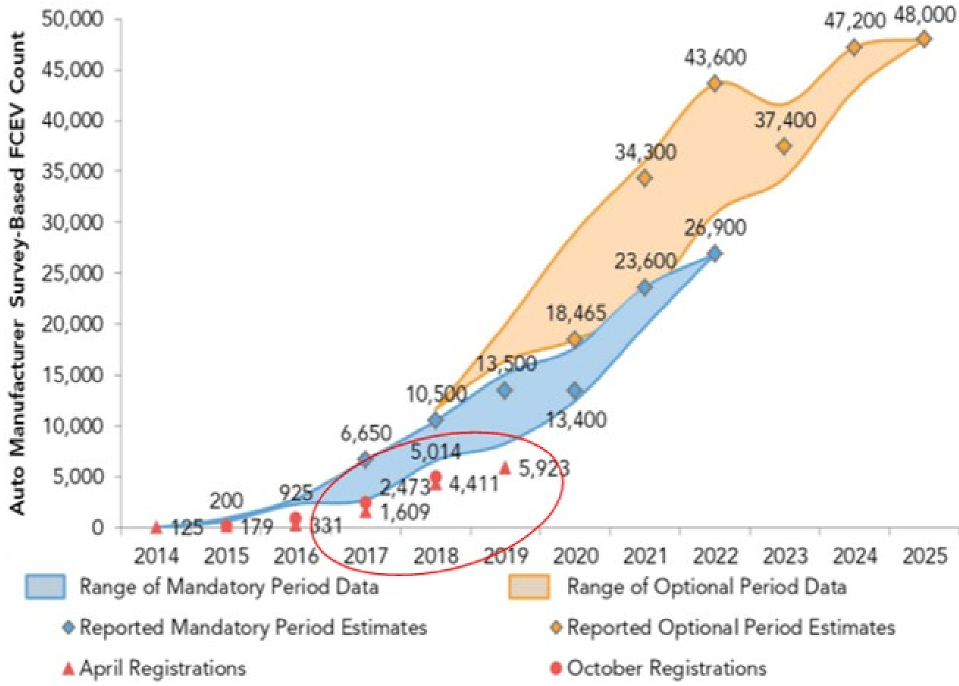
[52] CARB (2019). 2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development. https://ww2.arb.ca.gov/sites/default/files/2019-07/AB8_report_2019_Final.pdf

[53] California Energy Commission (2020). Renewable Hydrogen Transportation Fuel Production. https://cafcp.org/sites/default/files/Roadmap-for-Deployment-and-Buildout-of-RH2-UCI-CEC-June-2020.pdf

[54] Brandon and Kurban (2017). Clean Energy and the Hydrogen Economy. Physical Transactions of the Royal. https://royalsocietypublishing.org/doi/10.1098/rsta.2016.0400

is \$14-\$16 per kilogram and is composed of approximately 2/3 fossil H_2 and 1/3 renewable hydrogen.[55] Many early stations in California have experienced station outages due to short supply of hydrogen or equipment malfunction.[56]

Figure 19. Projected population and actual registrations of FCEVs in California.



To summarize, the market maturity and technology readiness of hydrogen FCEVs lags behind that of EVs in 2020. Table 11 provides a qualitative comparison of FCEVs, ICEVs, and BEVs across several dimensions. FCEV adoption in California has taken longer than initially anticipated and hydrogen availability and cost continue to be major barriers.[57] A shift towards largescale FCEV adoption is unlikely in the near-term (3-5 years) given that no major automaker beyond Toyota, Hyundai, or Honda has announced a research and development pathway for an FCEV. In contrast, nearly every major automaker and several startups are expected to release new EV makes and models in the next three years. Yet, the supremacy of EVs over FCEVs in the medium- and long-term is far from certain, especially for vehicle owners with operational or daily range needs that may be challenging to satisfy with EVs.

The companion *Energy Pathways Report* – assumes nearly 100% of LDVs in the Commonwealth need to be zero emission or near-zero emission by 2050; FCEVs may be a viable candidate technology, especially closer to 2050 when renewable hydrogen may be more available and cost-effective.

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[55] CARB (2019). 2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development. https://ww2.arb.ca.gov/sites/default/files/2019-07/AB8_report_2019_Final.pdf
[56] Ibid.
[57] Ibid.

Table 11. Qualitative comparison of ICEVs, BEVs, FCEVs.

Category	ICE	BEV	FCEV
Capital cost	$	$$	$$$
Fuel cost	$$	$	$$$
Refueling time	~5 min	10 min (DCFC) to 12 hrs (120V)*	~5 min
Long-range travel days	No Impact	High Impact	No Impact (infrastructure needed)
Station up-time	Reliable	Reliable	Sometimes unreliable
Adoption in first four years	N/A	~134,000	~6,000

* depends on battery size, state-of-charge, and charging power

5.3 Travel Demand Reduction and Mode Shift Strategies

Managing demand for mobility has the potential to support transportation decarbonization efforts through a variety of ways. Most directly, demand reduction strategies can eliminate trips taken in a personal vehicle by eliminating the need for a trip altogether or by shifting the model of travel from a personal vehicle to a shared vehicle or non-motorized mode such as walking or biking. As personal vehicles today are predominantly powered by fossil fuels, the avoidance of a trip using a personal vehicle in the near-term can eliminate emissions associated with a trip. While alternative modes may include those that use fossil fuels (e.g., a diesel bus or train), the shift of a trip to alternative modes often generates effectively no new emissions (e.g., bicycling, trip on existing transit) or can substantially lower the emissions intensity per trip (e.g., carpooling, new transit service). Mode shifting can also intersect with other social objectives: shifting trips to transit or shared rides can reduce congestion; replacing car trips with walking and biking can help improve physical health; and investment in public transportation can provide access to jobs, housing, and resources.

Trip mode selection is influenced by a number of factors including cost, travel time, accessibility, safety, and potential for physical fitness. A sampling of potential strategies that are capable of promoting mode shift by altering these factors are listed in Table 12. These range from pricing strategies that seek to increase the cost of driving (relative to other modes), and behavioral and transit strategies which aim to reduce demand for driving via the elimination of trips or shifting to alternative modes of transportation.

Table 12. Example strategies to promote mode shift.

Pricing Strategies	Behavioral Strategies	Transit Strategies
Fuel pricing (gas or carbon tax)	Work from home policies	Expanded transit services
VMT Fees	Ride sharing (park & ride, HOV lanes)	Low cost or free transit
Congestion fees	Employer-based Travel Demand Management	Transit-Oriented Development
Parking fees		Active transit facilities

5.3.1 Trends and Outlook in the Commonwealth

Population and economic growth in the Commonwealth in the past decade has increased demand for mobility services. The role of mobility demand in the future is uncertain, driven predominantly by the COVID-19 pandemic, but also uncertainty regarding the future prevalence of ride hailing services, microtransit, micromobility, and autonomous vehicles. Despite recent excitement in several of these areas, the deployment of these services at scale are highly uncertain and may take longer to achieve, if at all. The potential for mode shift strategies is not uniform across the Commonwealth due to different land use and development patterns, varying levels of access to public transit or active transit infrastructure and resources, and demographics.

The analysis of mode shift strategies described below was designed before and conducted during the emergence of the COVID-19 pandemic. The pandemic has created a number of near-term and long-term considerations for the future of mobility. It is unclear how the potential shift in professional service jobs to work from home (WFH) will impact future mobility demand, but, in the near term, there has been a measurable reduction in personal vehicle use.

5.3.2 Mode Shift Analysis

The EERPAT model, described in Section 4.2, was used to evaluate several scenarios around mode shift. This work builds off a prior report that looked at individual strategies to reduce GHG emissions in Massachusetts,[58] and examines several strategies also discussed and analyzed by MassDOT in its 2019 *Congestion in the Commonwealth* report. The analysis here explores packages of strategies that have the potential to achieve reductions in vehicle use at levels that would result in material statewide emissions reductions. These strategies are listed in Table 13, and comprise a theoretical package of transit management policies, VMT fees, and Urban Growth Policy. In this exploration, VMT fees are applied to all light-duty vehicles, including EVs.

*Table 13. Modeled EERPAT Variables. *Indicates assumption consistent with MassDOT EERPAT Report*

Policy	EERPAT Implementation
Reference Case	No change to current policies.
Transit Policy	Package of several demand management policies: *Congestion Charges** - Applied to currently tolled highways (I-90) at rates of $0.25/mile and $0.5/mile for Boston-MPO limited access highways. *Active Transportation** - Investment assumed to triple bicycle mode share from 2015 levels to 2030 and held consistent onwards. *Public Transit Growth** - Assume 2% annual increase in Vehicle-Revenue Mile per capita for all services. *Travel Demand Management* – Interventions assumed to reach employers with >100 employees, increasing workforce reached from 25% to 37%.*
VMT Fees	VMT Fee displaced a $0.24 state gas tax at modeled levels of 1 cent/mile, 5 cents/mile, and 10 cents per mile.
Densification Policy	Increase in proportion of households located in mixed-use areas. From 2020-2030, 80% of new households would be located in mixed use areas. After 2030, at least 90% of new households would be located in mixed use areas.

[58] Cambridge Systematics (2017). Application of the EERPAT Greenhouse Gas Analysis Tool in Massachusetts. https://www.mass.gov/doc/eerpat-report/download

Several long-term trends – increasing population, aging demographics, and economic growth – are all expected to drive demand for mobility services up in the future. In the absence of policy intervention (such as those detailed above), this increased mobility demand could result in an increase in VMT by 2050, as shown in Table 14. (While not insignificant, such an increase would be less than a third of the increase in VMT across the U.S. in the 35-years ending in 2015.) By 2050, EERPAT models a 22.6% increase in daily vehicle miles traveled (DVMT) for Massachusetts, despite only experiencing about 9.1% population growth. This level of growth in DVMT is consistent across all regions of the Commonwealth. Notably, despite larger population increases in MAPC North & West, modelled DVMT increases in these regions tend to be lower, in part, due to greater availability of public transportation options and denser built environments.

Table 14. Million Daily Vehicle Miles Traveled (DVMT) for EERPAT Analysis Regions for 2015 base year and 2050 reference scenario.

	Population (thousands)			DVMT (millions)			DVMT per capita		
RPA/County	2015	2050	Increase	2015	2050	% Increase	2015	2050	% Increase
Berkshire County RPC	142	127	-10.6%	3.4	3.7	8.4%	23.8	28.8	21.2%
MAPC: Suffolk	734	828	12.9%	8.7	11.3	30.4%	11.8	13.7	15.6%
MAPC: North & West	1758	2035	15.8%	35.5	43.0	21.1%	20.2	21.1	4.6%
MAPC: South	778	905	16.3%	18.1	23.6	30.2%	23.3	26.1	12.0%
Cape & Islands	268	171	-36.2%	8.3	6.5	-21.8%	31.0	38.0	22.4%
Central Mass.	566	655	15.7%	15.0	19.9	32.9%	26.4	30.4	14.9%
Franklin	76	67	-12.2%	2.3	2.6	11.3%	30.7	38.9	26.7%
Merrimack Velley	341	387	13.5%	7.3	9.4	28.5%	21.5	24.3	13.2%
Montachusett	244	240	-1.9%	6.0	7.4	23.7%	24.6	31.0	26.2%
Northern Middlesex	295	287	-2.9%	6.4	7.3	15.0%	21.6	25.6	18.4%
Old Colony	298	398	33.9%	9.6	12.9	33.8%	32.4	32.4	0.0%
Pioneer Valley	650	660	1.6%	13.4	16.5	23.1%	20.6	25.0	21.2%
Southern Mass	643	651	1.2%	14.9	18.5	24.4%	23.1	28.4	22.9%
Statewide	6792.4	7410.3	9.1%	148.9	182.6	22.6%	21.9	24.6	12.4%

5.3.3 Transit and Pricing Policy

The analysis using EERPAT indicated that in order to realize VMT reductions significant to represent a major, independent emissions reduction strategy, aggressive strategies would need to be successfully implemented. Table 15 shows the impact of various potential policy combinations on VMT. In all cases, the modeled strategies were unable to completely limit growth from baseline 2015 levels, let alone achieve a net decrease in VMT. VMT fees, which can be also interpreted as an average increase in the cost of driving per mile, needed to be large to have a significant effect on modelled behaviors. Depending on the efficiency (MPG) of a vehicle, the Commonwealth's current gas tax is equivalent in EERPAT modelling to a 0.5 – 1.5 cent VMT fee. Only fees 5 or 10 times that level—which at the higher end of that range would result in an increase in annual vehicle ownership costs of approximately $1,000, depending on vehicle usage[59]—appear to have the potential to deliver measurable and meaningful reductions in VMT (Table 15). These results tend to confirm the general

[59] Annual cost of ownership ranges from $7,000 - $11,000 according to AAA: https://newsroom.aaa.com/auto/your-driving-costs/

price-inelasticity of personal vehicle use, particularly outside of urban areas where fewer alternative modes exist.

The application in EERPAT of an aggressive transit policy package delivers a similar scale of VMT reduction. It is worth underscoring that the policies modeled in this case, particularly transit growth, are very ambitious, effectively resulting in a 70% increase in transit service. For the Metro-Boston region, such an increase would be at the upper end of those currently conceived, such as MassDOT's RailVision Alternative Six scenario (estimated to cost more than $30 billion).[60] VMT impacts of transit policy and the VMT fees were modelled here as additive, but it is important to note that such strategies may benefit from simultaneous implementation that is not reflected in the model. First, increasing the cost of travel without coincidental improvement in the accessibility and availability of alternatives can create a burden on those who are priced out or who might disproportionately incur the cost of roadway pricing strategies. Second, some roadway pricing strategies can be used to generate revenue for infrastructure projects to reduce congestion.

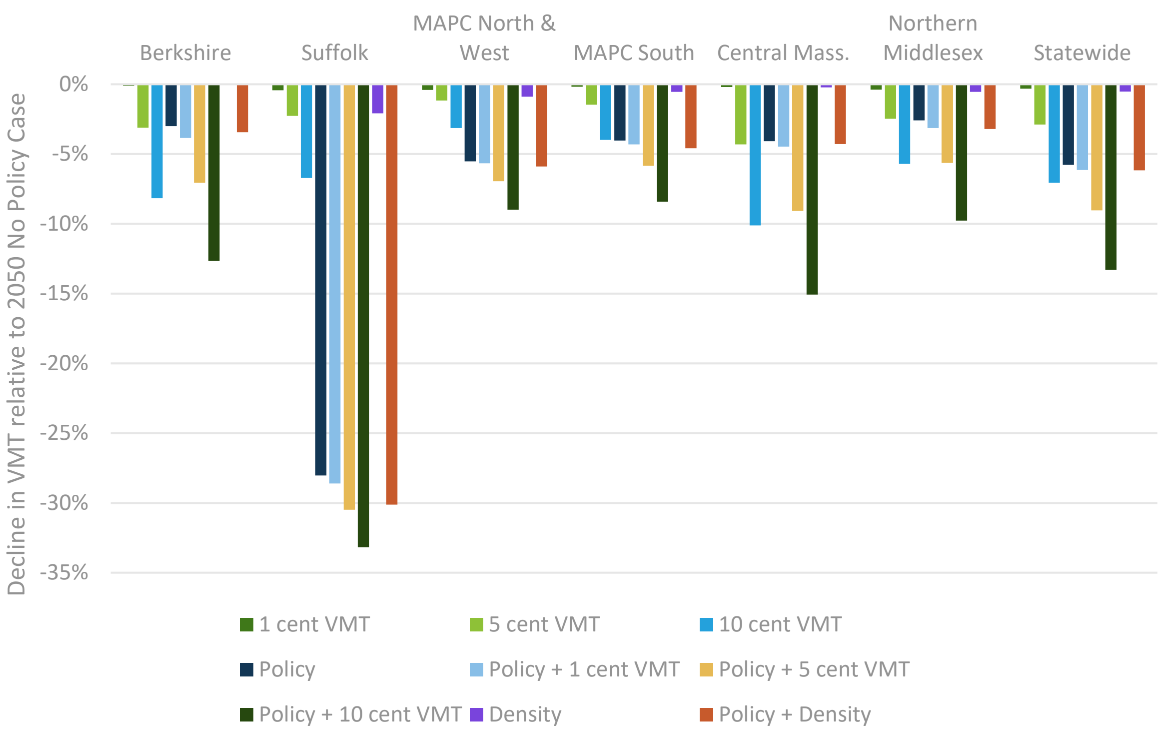
Table 15. Impacts of strategies on statewide Daily VMT (DVMT). Impacts of policies are show with respect to total DVMT, and compared to the 2015 base year, the 2050 no policy case, and as a proportion of the 2015-2050 growth.

Scenario	Million DVMT	Growth from 2015	Reduction from 2050 No Policy	Reduction in 2015-2050 growth
2015	148.9	0.0%	N/A	N/A
2050 No policy	182.6	22.6%	0.0%	0.0%
1 Cent VMT fee	182.0	22.3%	-0.3%	-1.7%
5 Cent VMT fee	177.3	19.1%	-3.0%	-15.6%
10 Cent VMT fee	169.7	14.0%	-7.6%	-38.2%
Transit Policy + No VMT fee	172.1	15.6%	-6.1%	-31.3%
Transit Policy + 1 cent VMT fee	171.4	15.1%	-6.6%	-33.3%
Transit Policy + 5 cent VMT fee	166.1	11.6%	-9.9%	-49.0%
Transit Policy + 10 cent VMT fee	158.3	6.3%	-15.4%	-72.1%
Density	181.7	22.0%	-0.5%	-2.6%
Transit Policy + Density	171.3	15.1%	-6.6%	-33.5%

The impact of such polices would be expected to vary by region. Figure 20 shows the change in VMT for the hypothetical policy scenarios described above. Notably, transit policy as modelled is most impactful in the Metro-Boston core of Suffolk County and, if coupled with roadway pricing strategies, becomes more impactful. Across other RPAs and statewide, a combination of roadway pricing and transit policy would be needed to achieve measurable reductions in VMT through demand reduction and mode shift strategies.

[60] E.g., MBTA Rail Vision (2019). https://www.mbta.com/projects/rail-vision

Figure 20. Change in VMT by region as a result of VMT fees and transit policy. Note some RPA's are omitted for simplicity. Policy and Density are used to respectively indicate the application of transit policy and densificiantion policy as described in Table 13.



5.3.4 Densification

The application of a policy to encourage mixed use new growth (80% of all growth from 2020-2030, and 90% onwards) had limited effect in VMT as shown in the density scenarios in Table 15. Such policies were most effective in Suffolk County (Boston) where existing infrastructure and patterns support such development. The limited impact of such a policy is due primarily to the fact that it only applies to new growth, and baseline growth trends represent relatively dense, transit-oriented development already. Further, historical trends in the model (such as higher incomes and mobility demand in some urban regions – compared to adjacent rural regions) may create an artefact that places upward pressure on VMT in certain regions. However, the allocation of growth to metropolitan regions generally reduced per capita VMT within those metropolitan regions and increased use of public transit in the model. This is consistent with prior work using EERPAT.[61]

5.4 Intersection of Electrification, Renewable Energy, and Travel

There are three overarching factors that influence decarbonization in the LDV sub-sector:

1. Carbon intensity of electricity supply used to power electric vehicles,
2. Pace and magnitude of vehicle electrification, and
3. Travel demand.

[61] RSG. State DOT Pilot Testing of the Energy and Emissions Reduction Policy Analysis Tool (2014).

The first item is explored in detail in the *Energy Pathways Report*, with the aggregate-annual share of renewable energy exceeding 95%, leading to very low carbon intensities of less than 20 kg CO_2/MWh.[62] The second and third items are assessed in detail in sections 5.1 and 5.3 respectively. The impact of fuel cell electric vehicles (discussed in section 5.2) could be considered analogous to vehicle electrification with appropriate changes to vehicle efficiency and carbon intensity with little impact on the overall results.

This section discusses how changes to the magnitude of the above three factors influence decarbonization of the LDV sector. In the *Energy Pathways Report*, the least-cost ("All Options") deep decarbonization pathway is built from the assumption that 98% of the LDV fleet can be electrified by 2050. Further, the EnergyPATHWAYS model allows residual ICE LDVs to be decarbonized with a zero-carbon gasoline fuel.

Given the potential challenges needed to meet this electrification target, it is worth assessing the bounds of EV adoption and mode shift. Despite the stark implications of such a high (98%) electrification target, the following conceptual exercise highlights the relative mitigation opportunities of electrification (more significant) compared to those of mode-shift and VMT reduction (relatively smaller).

Illustrating this dynamic, a conceptual exercise could assume that the light duty fleet needs to achieve a 90% emissions reduction by 2050 and does not rely on a carbon neutral fuel. We apply the methods of Alarfarj et al.[63] to Massachusetts-specific travel numbers and this emissions target to develop a vehicle electrification frontier as a function of the overall target and grid carbon intensity (Figure 21) and a travel budget frontier as a function of electrification and grid carbon intensity (Figure 22).

The slanted contour lines in Figure 21 represent the level of EV penetration within the LDV stock in Massachusetts necessary for achieving a given total LDV CO_2 emissions (y-axis) under a specific grid carbon intensity (x-axis). This figure emphasizes the need to achieve both near complete vehicle electrification and grid decarbonization to achieve deep decarbonization levels aligned with those in the pathways in the *Energy Pathways Report*.

Figure 21 assumes a fixed carbon budget for the LDV sector of two million metric tons CO_2e (approximately 10% of both 1990 and 2017 emissions for LDVs).[64] The contour lines in Figure 22 represent the maximum number of vehicles miles traveled (VMT) needed to achieve that target given a specific carbon intensity (y-axis) and EV share of the total VMT (x-axis). The baseline travel budget was assumed to be 67 billion VMT (148 million daily VMT), a 22.6% increase from 2015 levels. The basis for this calculation is presented in 5.4.2.

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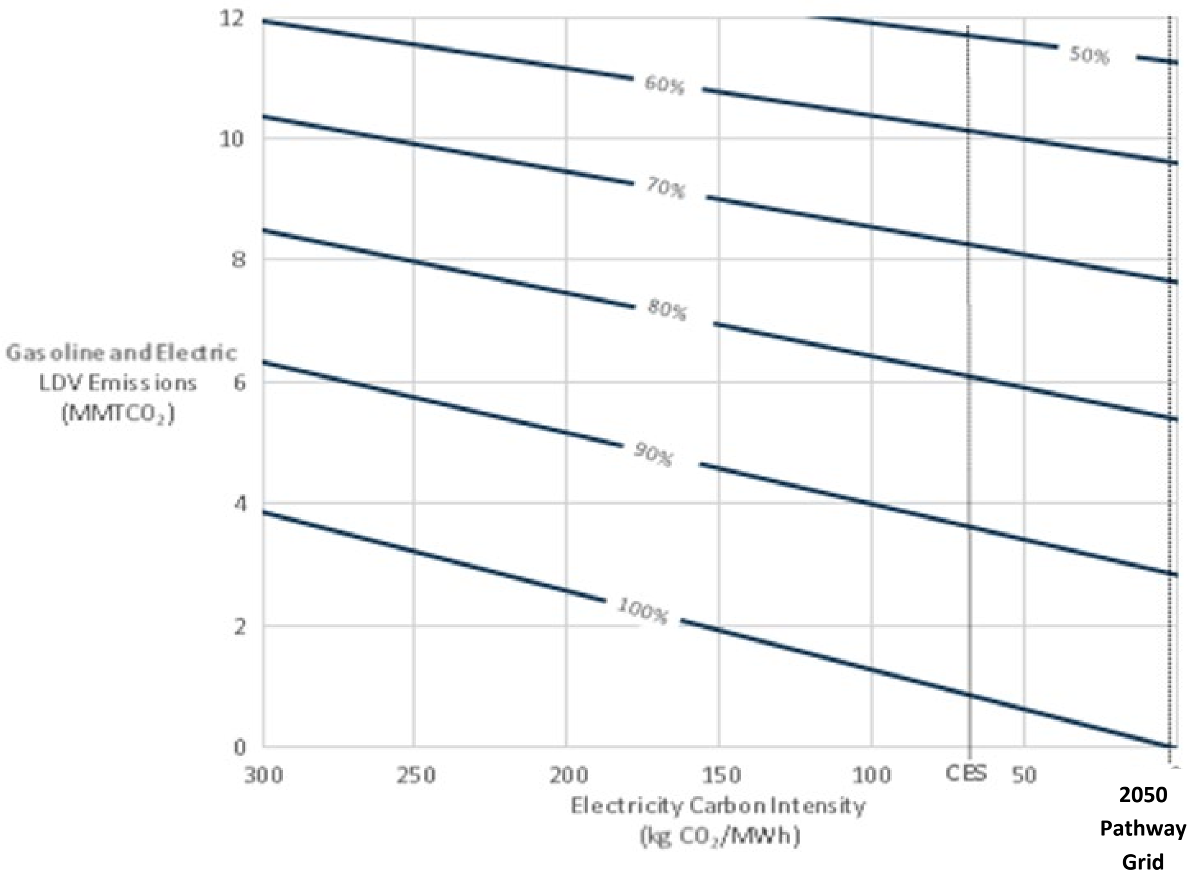
[62] The Clean Energy Standard (CMR 7.75) currently stipulates that at least 80% of Massachusetts' purchased electricity come from carbon free sources by 2050. The All Options Pathway, for example, is at 3.7 grams/kWh in 2050.

[63] Alarfaj et al. Decarbonizing US passenger vehicle transport under electrification and automation uncertainty has a travel budget. *Environmental Research Letters*. (2019). https://doi.org/10.1088/1748-9326/ab7c89. This study focuses on national emission targets and travel budgets, and assesses the potential and limits of the above factors in achieving those targets recognizing uncertainty in technology performance and automation.

[64] For the purposes of this exercise, this budget includes both direct emissions from ICE vehicles and the emissions generated for the production of electricity used by EVs. The latter is typically accounted for in the Electricity generation sector. Thus, the overall transportation sector target would be in excess of 90% and depend on the level of EV penetration shown in the figure.

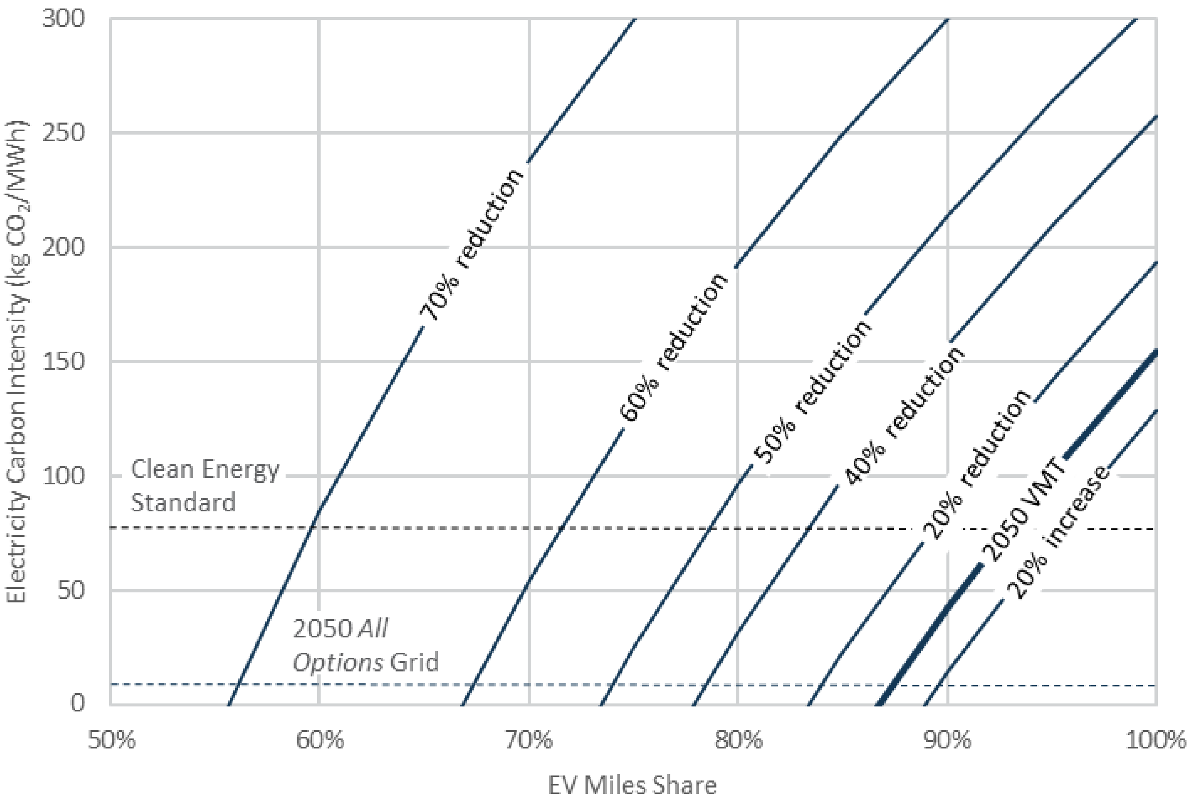
Figure 21. Electric vehicle frontier for assuming demand of 66 Billion VMT in 2050. 1990 emissions for this subsector were approximately 20 $MMTCO_2$ while 2017 emission were approximately 21 $MMTCO_2$. Dashed lines represent carbon intensity of the grid under the 2050 values for the Clean Energy Standard (CES) and the All Options modeled pathway in the Energy Pathways Report.



If we assume the grid achieves the level of emissions in the *All Options* pathway described above and in the *Energy Pathways Report*, then the share of EV miles would need to be approximately 87% of total VMT. The reason the EV miles share is lower than the 90% emissions reduction target is because of improved efficiencies in the ICE vehicle stock (assumed to reach 36.4 mpg in 2050).

If supplied electricity only reached levels stipulated by the Clean Energy Standard (as written before the amendments made in July 2020, which slightly, but not dramatically impact this analysis), the EV share would need to increase to about 93% or 2050 VMT would need to be reduced by approximately 25%. This is approximately 8% below today's levels. While the VMT contours in the figure appear to indicate drastic reductions, they emphasize that EV penetration is a critical decarbonization strategy: if less than 75% of miles driven were electric vehicle miles, total annual VMT would need to be halved to achieve the emissions target under the All Options (95% renewable grid).

Figure 22. Travel budget frontier for a 2 MMTCO$_2$ 2050 emissions target for electric and gasoline emissions from LDV use. Contour lines represent VMT levels needed to achieve the target at the EV mile share (x-axis) and grid carbon intensity (y-axis). Dashed lines represent carbon intensity of the grid under the 2050 values for the Clean Energy Standard (CES) and the All Options modeled pathway in the Energy Pathways Report. For comparison purposes, the 20% reduction contour line is approximately equal to 2015 VMT levels. Methods and vehicle efficiency assumptions were obtained from Reference.



Importantly, achieving a 50% reduction in VMT represents an impact three to four times larger than that of the aggressive mode-shift strategies modeled in EERPAT and discussed above. Poignantly, however, the most aggressive lockdowns responding to the COVID-19 pandemic in April 2020 did result in about a 60% decline in DVMT.[65] Ultimately, this underscore than achieving a reduction in VMT at the scale needed to obviate significant light-duty vehicle electrification represents a dramatic disruption to people's daily lives (far more so, for example, than needing 20 minutes to recharge a battery rather than five minutes to refill a gas tank). While the analysis above is presented with a 2050 target in mind, the results provide insights for interim years emphasizing that VMT reduction strategies can be effective at reducing emissions when EV shares are still low – such as in 2030.

The results from this exercise emphasize three key strategies for reducing emissions from LDV travel:

- Maximizing the share of BEVs and BEV miles in the LDV transportation sector is essential for achieving aggressive emissions reduction targets.
- Reducing VMT supports ambitious decarbonization targets by easing some requirements in the electricity sector and by reducing emissions in interim years.

[65] MassDOT Mobility Dashboard. https://mobility-massdot.hub.arcgis.com/

- Providing near-decarbonized electricity for BEV charging is essential for achieving deep decarbonization goals. This can be accomplished by reducing the overall carbon intensity of the grid, and by optimizing EV charging though flexible systems and rates that incentivize charging when carbon-free energy supplies are abundant and low cost.

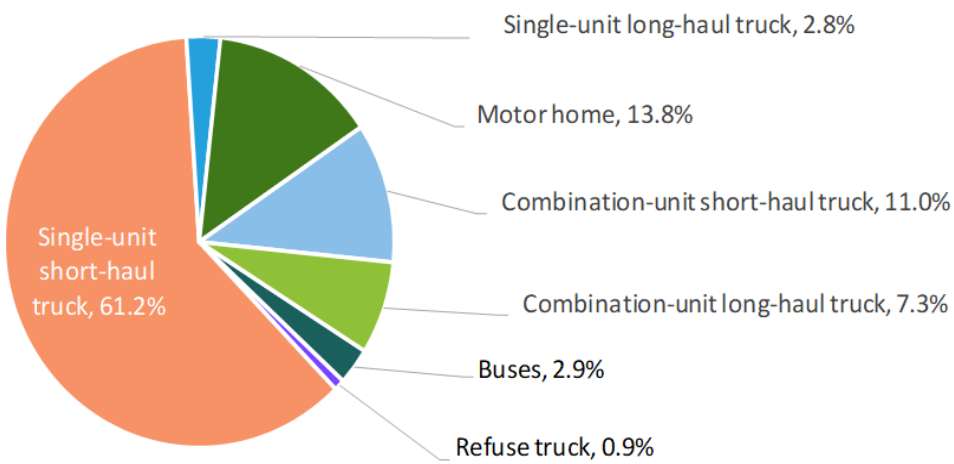
6 Medium- and Heavy-Duty Vehicle Sub-Sector

This Chapter describes key technology and behavioral transformations needed to reach deep decarbonization in medium- and heavy-duty (MDHD) vehicles. For this analysis, MDHD vehicles are defined as vehicles over 10,000 pounds on a gross vehicle weight rating.

6.1 Trends in Heavy-Duty Sub-Sector

According to the Massachusetts Department of Environmental Protection (MassDEP), the Commonwealth has an estimated 138,000 MDHDVs, accounting for 3% of all on-road vehicles.[66] Figure 23 summarizes segments, by vehicle category. Single-unit short-haul trucks account for over 60% of all registered MDHD vehicles in the Commonwealth. The majority of MDHD vehicles are diesel powered (71%), and the remainder are gasoline powered (29%). MDHD vehicle emissions have been growing over time. According to the *Massachusetts Annual GHG Emissions Inventory: 1990-2017*, CO_2 emissions from MDHD vehicles nearly doubled between 1990 and 2017, while Transportation Sector emissions increased by only 14%.[67]

Figure 23. Fraction of MDHD vehicles registered in Massachusetts, by vehicle category out of the estimated 138,000 registered vehicles.



MDHD vehicles account for a disproportionate share of air pollutants and GHG emissions compared to other transportation sub-sectors. For example, in 2017 MDHD vehicles accounted for only 6% of annual on-road VMT in the Commonwealth, but 29% of CO_2 emissions from on-road vehicles.[68] Moreover, because MDHD vehicles

[66] Includes estimates from the Department of Environmental Protection used in the Commonwealth's Diesel Inventory. https://www.mass.gov/doc/appendix-c-massachusetts-annual-greenhouse-gas-emissions-inventory-1990-2017-with-partial-2018/download

[67] MassDEP (2020). Appendix C: Massachusetts Annual Greenhouse Gas Emissions Inventory: 1990-2017, with Partial 2018 Data. https://www.mass.gov/doc/appendix-c-massachusetts-annual-greenhouse-gas-emissions-inventory-1990-2017-with-partial-2018/download

[68] Estimated by dividing heavy-duty truck CO_2 emissions by CO_2 emissions from passenger cars, light-duty trucks, heavy-duty trucks, motorcycles.

are more likely to operate in fleets, engaging a single fleet manager can have a multiplicative effect on emissions reductions.

Vehicle and freight system efficiency improvements offer the most promising near-term GHG emission reductions solutions for MDHD vehicles. Such improvements include hybridization, improvements in aerodynamics, reduced rolling resistance for tires, truck weight reduction, enhanced powertrain efficiency, and freight systems that reward efficiency. Yet, despite their promise, these improvements alone cannot produce the deep GHG reductions needed in the MDHD sub-sector to meet GWSA goals.[69] Thus, this section focuses on fuel switching to electrification, hydrogen, biofuels, and electrofuels.

6.2 Electrification

MDHD electrification, particularly of transit buses, is already underway across the Northeast. In 2019, the Massachusetts Bay Transportation Authority (MBTA) added five zero-emission, battery-electric buses to the Silver Line fleet.[70] Worcester Regional Transit Authority (WRTA) and the Pioneer Valley Transit Authority (PVTA) have deployed nine electric Proterra buses, Martha's Vineyard Transit Authority has recently put six new BYD Coach & Bus electric transit buses into operation, and other transit authorities are following suit.[71] In the Northeast region in general, several fleets are aggressively pursuing electric buses. For example, New York City's MTA operates the nation's largest all-electric transit bus fleet. MTA purchased 15 battery electric buses, with a plan to purchase 500 new buses serving all five boroughs in its 2020-2024 Capital Plan.[72]

6.2.1 Outlook in the Commonwealth

In July of 2020, Governor Baker signed a memorandum of understanding (MOU) committing the Commonwealth to work collaboratively with a coalition of states to accelerate the market for zero emission medium- and heavy-duty vehicles.[73] As part of the MOU, the states indicated a plan to adopt the California Advanced Clean Trucks Rules. The Advanced Clean Trucks Rule is a regulatory requirement for medium- and heavy-duty vehicle manufacturers to achieve an increasing percentage of zero-emission vehicle sales relative to their total sales. These requirements vary by vehicle class and will require the following targets by 2035: 55% of Class 2b-3 trucks; 75% of Class 4-8 trucks; and 40% of truck tractors. The regulation also requires fleet owners with 50 or more trucks to report on their fleet operations, which will help shape future strategies for

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[69] For example, even the most efficient internal combustion engines today are only capable of around converting 40% of gasoline's energy to propulsion, compared to an average of 15-20% for most ICEVs. https://www.thedrive.com/tech/18919/toyota-develops-worlds-most-thermally-efficient-2-0-liter-engine

[70] Mass Transit Magazine (2019) First zero-emission, battery-electric buses join Massachusetts Bay Transportation Authority. https://www.masstransitmag.com/bus/vehicles/hybrid-hydrogen-electric-vehicles/press-release/21091005/massachusetts-bay-transportation-authority-mbta-first-zeroemission-batteryelectric-buses-join-massachusetts-bay-transportation-authority#:~:text=The%20Massachusetts%20Transportation%20Authority%20(MBTA,an%20event%20with%20Massachusetts%20Gov.

[71] Vineyard Gazette (2020). Study Finds Electric Bus Charging Station Would Not Add to Congestion. https://vineyardgazette.com/news/2020/06/11/tstudy-finds-electric-bus-charging-station-would-not-add-congestion

[72] MTA Capital Program (2019). MTA Capital Program 2020-2024: Rebuilding New York's Transportation System. https://new.mta.info/sites/default/files/2019-09/MTA%202020-2024%20Capital%20Program%20-%20Full%20Report.pdf

[73] U.S. States. (2020). Multi-State Medium- and Heavy-Duty Zero Emissions Vehicle Memorandum of Understanding. https://www.nescaum.org/documents/multistate-truck-zev-governors-mou-20200714.pdf

further deploying ZEV trucks.[74] Several issues discussed below, such as the anticipated evolution of vehicle availability and operability, as well as electric infrastructure requirements, especially for depots housing multiple vehicles, represent both opportunities and barriers that policy can both ease and exploit as the technology continues to mature.

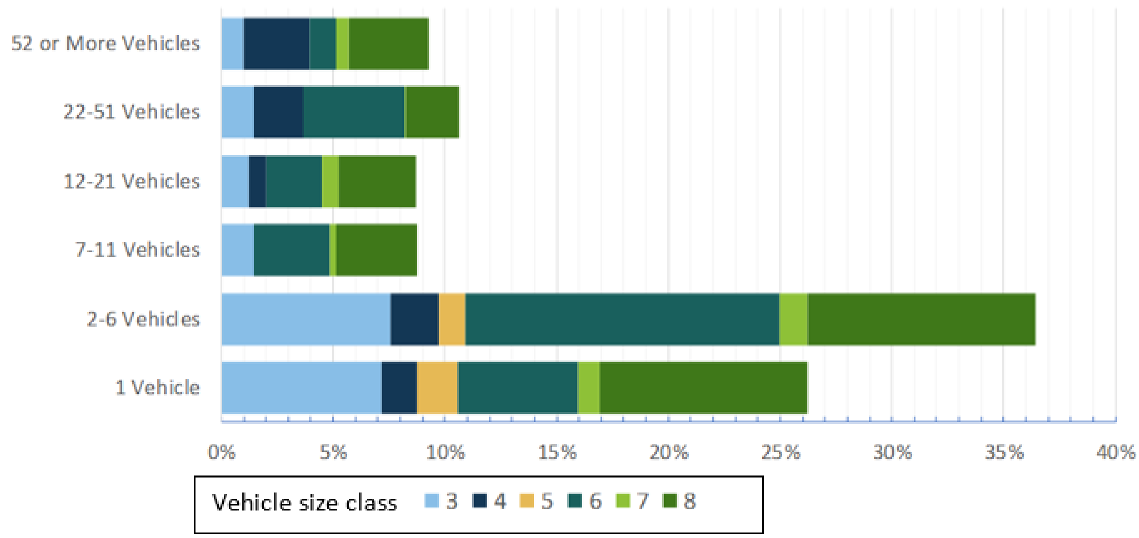
6.2.2 Model Availability

Electric MDHD vehicles remain in a relatively early stage of market maturity in the United States. The energy and volumetric density of batteries creates a tradeoff between vehicle range, cargo, and passenger capacity. The Zero Emission Technology Inventory (ZETI) tool from CALSTART lists 11 medium-duty electric truck models available today with 67 options expected by 2023; four heavy-duty electric truck models available today with 19 by 2023; two cargo vans available today with nine by 2023; and 34 electric transit bus models available today with 37 options expected by 2023.

6.2.3 Electricity Distribution System

Electric MDHD vehicles have potential to stress the electrical distribution system if charging is geographically concentrated and unmanaged. The primary solutions to mitigate these stresses include managed charging and near-term electrical infrastructure planning that anticipates, in particular, future MDHD charging needs. Regarding the latter, Vehicle Inventory and Use Survey data[75] for Massachusetts suggests the Commonwealth already has a relatively dispersed geographic fleet, with 63% of non-bus MDHD vehicle fleet vehicles parked in parking lots or depots with six or fewer vehicles (sum of the bottom two bars of Figure 24), and only 37% parked in lots or depots with more than six vehicles (sum of the top four bars of Figure 24). Regardless, this is an important issue for policy-makers to address particularly for urban transit fleets.

Figure 24. Fraction of vehicles in each fleet size category for Class 2b – Class 8 vehicles.



[74] California Air Resources Board (2020). Advanced Clean Trucks Fact Sheet. https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet

[75] The VIUS is a nationally representative survey of over 100,000 fleet vehicles conducted by the U.S. Census Bureau.

Electric MDHD vehicles typically charge at higher power levels than LDVs due to the larger battery size. Table 16 provides examples of the charge time (in hours) for several different electric vehicle types and power levels. The average battery size for each vehicle type was taken from CALSTART.[76] The estimated charge times assume the battery charges 80% of its rated capacity. As shown, vehicles with the largest batteries (e.g., Tractor Truck, Bus – Coach) have charge times over 8 hours if using a 30 kW fast charge. Only at 500 kW charging do all vehicles have an estimated charge time of less than an hour. Particularly in the near-term, as electric MDHD technology is maturing and improving, this data suggests that MDHD routes and vehicles-per-route may require adjustment (potentially, shorter routes and/or more vehicles assigned per route) to allow for sufficient charge times. On route charging infrastructure can alleviate the need for both.

Table 16. Examples of estimated time to charge (in hours) by vehicle type and power.

Electric Vehicle	Avg Battery Size (kWh)*	Avg Charge Speed for 80% Charge (hrs)				
		30 kW	50 kW	150 kW	350 kW	500 kW
Bus - Coach	336	8.9	5.4	1.8	0.8	0.5
Bus - School	143	3.8	2.3	0.8	0.3	0.2
Bus - Shuttle	101	2.7	1.6	0.5	0.2	0.2
Bus - Shuttle, Bus - Transit	150	4.0	2.4	0.8	0.3	0.2
Bus - Shuttle, Delivery	126	3.3	2.0	0.7	0.3	0.2
Bus - Shuttle, Truck	127	3.4	2.0	0.7	0.3	0.2
Bus - Transit	315	8.4	5.0	1.7	0.7	0.5
Delivery	154	4.1	2.5	0.8	0.4	0.2
Delivery, Food Truck	128	3.4	2.0	0.7	0.3	0.2
Delivery, Refuse	143	3.8	2.3	0.8	0.3	0.2
Delivery, Tractor, Truck	485	12.9	7.8	2.6	1.1	0.8
Delivery, Truck	232	6.2	3.7	1.2	0.5	0.4
Panel Van	72	1.9	1.1	0.4	0.2	0.1
Refuse	256	6.8	4.1	1.4	0.6	0.4
Refuse, Tractor, Truck	160	4.3	2.6	0.9	0.4	0.3
Truck	141	3.8	2.3	0.8	0.3	0.2

6.2.4 Reduction in Payloads

Loss of payload capacity in terms of weight or volume, due to the installation of large and heavy batteries, can translate directly into cost increases for MDHD vehicles since more vehicle-miles will be needed to perform the same service. For example, an electric semi tractor-trailer requires a battery that weighs 11,000—14,600 lbs at 200—150 Wh/kg.[77] However, recent studies suggest the payload reduction in electric trucks is a relatively minor barrier. A paper by researchers at Carnegie Mellon University estimated that electric semi-trucks could support the payload needs of 93% of current freight trucks.[78]

[76] CALSTART (2020). HVIP Resources. https://www.californiahvip.org/
[77] Sripada S., and Viswanathan, V. (2018). Quantifying the Economic Case for Electric Semi-Trucks. ACS Energy Lett. 2019, 4, 1, 149–155.
[78] Ibid.

6.3 Hydrogen in Medium-Duty and Heavy-Duty Vehicles

Limited numbers of hydrogen fuel cell MDHD vehicles are on the road today and are primarily demonstration vehicles such as buses, drayage trucks, delivery trucks, and semi-trucks. Fuel cell buses have been in operation in California since 2000, when Sunline Transit began a demonstration of an early generation fuel cell bus.[79] Recently, several vehicle suppliers – such as Kenworth, Nikola, Toyota – have made announcements about plans for producing hydrogen fuel cell trucks.

Based on their experience of advancing hydrogen infrastructure and FCEVS, the California Air Resources Board suggests light-duty hydrogen fuel cell sales should be prioritized before MDHD hydrogen fuel cells to help drive down costs (see call-out box).

THE PATH FORWARD WITH HYDROGEN FUEL CELL HEAVY-DUTY VEHICLES:
"Because of the greater volume of light-duty vehicles, developing a market for hydrogen-fueled passenger cars (which begins with developing the associated hydrogen fueling network) can help fuel cell production reach large scale faster. Cost savings for fuel cells in light-duty vehicles can directly translate to medium and heavy-duty vehicles, as several manufacturers have already demonstrated by using the same fuel cell stack in vehicles across all of these sectors."

- California Air Resources Board *2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development,* p. 9.

6.4 Low Carbon Liquid Fuels in Medium-Duty and Heavy-Duty Vehicles

As described in the *Energy Pathways Report* and noted in Section 2.3 above, a common upper bound of bioenergy consumption is the resources identified by the Net Zero America Project at Princeton University, which identified 12 quads as the limit on U.S. biomass production without new land under cultivation for purpose grown energy crops. This estimate was derived from the 2016 U.S. Department of Energy Billion Ton Study Update. After competing uses of these resources (chemicals and bioplastics) are accounted for, Massachusetts' population-weighted share for this is approximately 41 TBtus per year. However, this estimate does not integrate subsequent industry standards advanced by the Roundtable for Sustainable Biomaterials and International Carbon and Sustainability and Carbon Certification. A separate nationwide assessment indicates that the economically-recoverable bioenergy production potential is only about 15% of the Billion Ton Study.[80] A pathway of waste oil-based fuels could provide a nationwide total of 1.3 billion gallons per year nationwide.[81]

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[79] FTA. (2001). Sunline Transit Agency Final Report (No. CA-26-7022). https://www.energy.gov/sites/prod/files/2014/03/f10/sunline_final_report1.pdf
[80] Parker, N. (2012) Spatially-explicit biofuel supply projection for meeting the renewable fuel standard, Journal of the Transportation Research Board. https://doi.org/10.3141%2F2287-09
[81] Morrison, G. et al. (2014). Comparison of supply and demand constraints on U.S. biofuel expansion. Energy Strategy Reviews. DOI: https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1016%2Fj.esr.2014.09.001

The biofuel potential estimates above do not reflect the potential for imported biomass or biofuel production from alternative sources like algae. However, the algae industry has recently shifted its focus from fuels to food due to better economic returns and sustainability outcomes. [82] [83] Additionally, other potential carbon neutral liquid fuels – such as electrofuels – could be economically viable fuel in the long-term. [84] Electrofuels are carbon-based fuels produced using electricity from carbon dioxide (CO_2) and water. Electrofuels are also known as power-to-gas/liquids/fuels, e-fuels, or synthetic fuels. As detailed above, this report estimates the limited potential for low carbon liquid fuels in Massachusetts. This suggests that, if they become viable at scale, these fuels should be used in highly targeted sub-sectors, such as aviation and potentially marine, rail, and heavy-duty vehicles. Additionally, the estimates suggest the need to continue developing technology and behavioral strategies beyond low carbon liquid fuel.

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[82] Walsh, M.J. et al. (2017). Financial tradeoffs of energy and food uses of algal biomass under stochastic conditions. Applied Energy. DOI: https://doi.org/10.1016/j.apenergy.2017.08.060

[83] Walsh, M.J. et al. (2016). Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. Environmental Research Letters. DOI: https://iopscience.iop.org/article/10.1088/1748-9326/11/11/114006

[84] Brynolf, S. et al. (2018) Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews. DOI: https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1016%2Fj.rser.2017.05.288

7 Other Sub-Sectors: Aviation, Marine, Rail

This Chapter describes fuel and vehicle technology options for decarbonizing aviation, marine, and rail sub-sectors in the Commonwealth. Broadly, the market maturity of decarbonization technologies lag that of LDVs and even MDHD vehicles. As noted above, this chapter does not include energy systems modeling. Rather, the focus is on characterizing the nascent market technologies that could lead to deep reductions in GHGs in the long-term. This is needed given the large uncertainties in development pathways for the sub-sectors.

7.1 Aviation

The Commonwealth of Massachusetts has 22 commercial service and general aviation airports that served a total of 21 million enplaned passengers in 2019 per year, of which 98% were from Boston.[85] The energy efficiency of narrow-body aircraft has increased steadily[86] at about 2% per year and is expected to continue increasing into the future. However, these rates have been outpaced by the anticipated growth in demand for air travel before the COVID-19 pandemic. In Massachusetts, the aviation sector is the fastest growing transportation sub-sector,[87] producing 12% of the Commonwealth's transportation GHG emissions in 2017. Even after accounting for the impact of COVID-19 on air travel, the Federal Aviation Administration forecasts[88] revenue passenger-miles to increase by 2.5% per year on average between 2020 and 2040.

The future of decarbonizing aircraft across a variety of fuels is in early stage development. In the sub-sections below, a high-level review of aviation decarbonization technologies are described. The largest source of carbon reduction is likely from sustainable aviation fuel (SAF). Given the low margins and high level of competition between airlines, it is not expected that the carriers will adopt SAF without compliance requirements. Massachusetts has limited jurisdiction over domestic flights and no jurisdiction over international air travel. However, even with limitations in commercial sustainable aviation fuel production capacity, it is recommended that the Commonwealth continue to study the aviation sector to explore innovative jurisdictionally-viable methods by which the Commonwealth can work to catalyze effective solutions.

7.1.1 Aviation Electrification

In the last decade, the aerospace industry has seen the emergence of all-electric aircraft propulsion systems.

Table 17 summarizes the number of active electric aircraft projects. The major categories of electric aircraft from smallest to largest include: light sportcraft, light, electric vertical takeoff and landing, and narrow body. As indicated in

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[85] Bureau of Transportation Statistics (2020) T-100 Market (All Carriers). https://www.transtats.bts.gov/Tables.asp?DB_ID=111&DB_Name=Air%20Carrier%20Statistics%20%28Form%2041%20Traffic%29-%20All%20Carriers&DB_Short_Name=Air%20Carriers

[86] Schäfer et al. (2016). Costs of mitigating CO_2 emissions from passenger aircraft. Nature Clim. Change 6, 412–417. https://www-nature-com.ezproxy.lib.gla.ac.uk/articles/nclimate2865

[87] MassDEP (2020). Appendix C: Massachusetts Annual Greenhouse Gas Emissions Inventory: 1990-2017, with Partial 2018 Data. https://www.mass.gov/doc/appendix-c-massachusetts-annual-greenhouse-gas-emissions-inventory-1990-2017-with-partial-2018/download

[88] FAA (2020). FAA Aerospace Forecast. https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/FY2020-40_FAA_Aerospace_Forecast.pdf

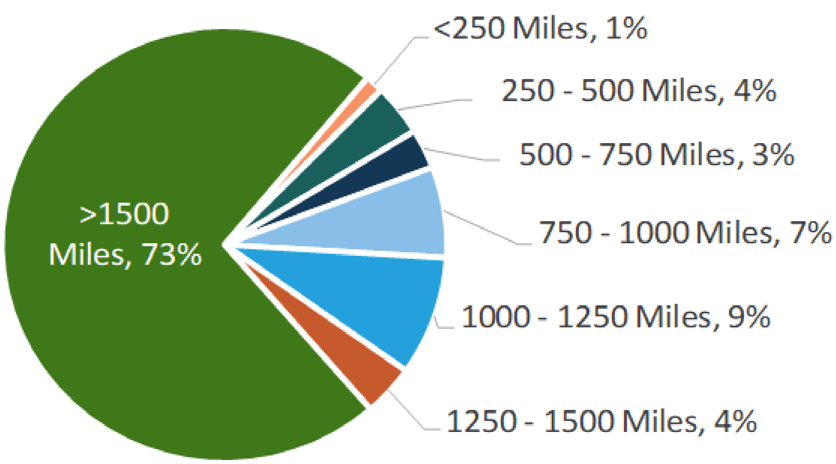
Table 17, electric propulsion is currently targeted at small aircraft with fewer than ten seats, although some narrow body planes with up to 150 seats are in development phases.[89]

Table 17. Number of all-electric aircraft, by stage of development[90]

Aircraft Category	Projects in Development Phase	Projects in Demonstration Phase	Projects in Concept Phase	Average Number of Seats of Projects
Light-Sport Aircraft	4	2	0	1.9
Light	5	8	0	2.3
Vertical Takeoff and Landing	24	1	2	2.8
Narrow body	3	0	7	69

Figure 25 provides a breakdown the fraction of passenger-miles by trip distance for flights departing Massachusetts. As shown, the greatest number of passenger-miles are in flights greater than 1,500 miles in length. As discussed in detail in Gnadt et al. (2019), electric aircraft with similar passenger capacities as today's commercial jets are infeasible with current battery technology. Flights of 500 nautical miles with a narrow-body electric aircraft would require over a three-fold increase in battery pack specific energy, from approximately 250 Wh/kg today to 800 Wh/kg.[91] A research group funded by the Department of Energy, Battery500 Consortium, recently announced achieving a 350 Wh/kg battery with 350 cycles (DOE, 2020).[92] To summarize, batteries with significantly higher specific energy and lower cost, coupled with further reductions of costs, are necessary for catalyzing an economically-viable all-electric aircraft industry. For lighter all-electric aircraft, eliminating AvGas fuel, the last source of transportation fuel lead, carries significant air quality benefits, even if the associated carbon reduction will be modest.

Figure 25. Share of passenger-miles by trip length departing from Massachusetts airports.



[89] Gnadt et al. (2019) Technical and environmental assessment of all-electric 180-passenger commercial aircraft. Progress in Aerospace Sciences, 105, pp. 1-30.
[90] Ibid.
[91] Schafer et al. (2019) Technological, economic, and environmental prospects of all-electric aircraft. Nature Energy, 4, pp. 160-166. https://www.nature.com/articles/s41560-018-0294-x
[92] U.S. DOE (2020) Battery500: Progress Update. https://www.energy.gov/eere/articles/battery500-progress-update

7.1.2 Hydrogen for Aviation

As with LDVs and MDHD vehicles, hydrogen can either be combusted directly in a jet engine or used to power a fuel cell. Indeed, several demonstration hydrogen aircraft have been built worldwide to date. A recent study co-funded by the European Union finds that hydrogen combustion in flight could reduce climate impact by 50% to 75%, and fuel-cell propulsion by 75% to 90%.[93] Further, the study finds that hydrogen aircraft are best suited for commuter, regional, short-range, and medium-range aircraft. The strongest market segments overlap with those of electric aircraft. However, hydrogen aircraft carry higher operating costs with longer refueling periods that reduce operating block hours and seating capacity tradeoffs with larger onboard hydrogen storage tanks. Establishing a parallel energy system to carry liquified H2 that needs to be implemented at dozens of airports simultaneously would be difficult and costly to execute. Hydrogen has fewer air quality emissions such as particulate matter. NOx emissions persist.

7.1.3 Low Carbon Liquid Fuels

As noted in Chapter VI, under a population-weighted share allocation of biomass, Massachusetts would have a theoretical maximum yield at around two billion gallons of domestically-produced zero- or near-decarbonized liquid fuel per year. Please note that this significant volume does not factor in all the sustainability requirements that aviation stakeholders prefer such as non-crop based feedstocks. For comparison, in 2015 Massachusetts consumed 300 million gallons of jet fuel and is projected to use around 400 million gallons by 2050 in the Reference scenario. Current and 2050 jet fuel demand equate with approximate 3-4 full size dedicated SAF production plants.

Both jet fuel and fuels relevant for marine and rail were represented in the modeling underlying the *Energy Pathways Report* which used an identical population-weighted share assumption. In general aviation and marine sectors dependence on liquid fuels is maintained in the analysis. These transportation types are generally the most expensive to electrify. By 2050, aviation demand is met by synthetic fuels derived from local hydrogen and captured CO_2, and by imported biomass-sourced and synthetic fuels. For reference, the least costly SAF pathway is Hydro-processed Esters and Fatty Acids (HEFA) which currently carries a 200% premium vs fossil jet and Power-to-Liquid is estimated to carry a 1500% premium or more

7.2 Rail

Diesel locomotives account for less than 0.5% of transportation GHG emissions in the Commonwealth, but are a major source of particulate matter pollution along their tracks. In Massachusetts, fifteen Regional Transit Authorities (RTAs) provide public transportation service to millions of riders each year.

7.2.1 Rail Electrification

Trains can be electrified using either overhead line electrification (OLE) or batteries that charge at regular intervals. A large fraction of the Amtrak Northeast Corridor already uses a variant of OLE. The 2019 MBTA *Rail*

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[93] McKinsey (2020) Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050. https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

Vision study included exploration of a fully electric commuter rail,[94] which has the advantage of greater efficiency and greater acceleration than diesel trains.[95] Estimates for OLE capital costs range from a low of $2 million per track-mile to a high of $8.5 million per track-mile for the lines.[96] Additional costs could result from the locomotive replacement. Beyond the cost concerns, rail powered by OLE incurs other risks, notably that any disruption or damage to the external infrastructure source can cause delays on an entire rail system. Battery electric trains are attracting some attention both in the United States and abroad.[97] Battery electric rail uses overhead lines and regenerative braking to recharge batteries for stretches between overhead lines. To date, no battery electric trains have been used in the Commonwealth. For either electrified rail or battery electric trains, the displacement of diesel along tracks would result in a reduction of particulate matter pollution.

7.2.2 Hydrogen for Rail

Hydrogen has begun to emerge as a potential fuel source for rail, although most early demonstrations have occurred outside the United States. In 2015, the international train manufacturer, Alstom, and Canada-based Hydrogenics partnered to develop a fuel cell locomotive.[98] Following successful testing of the hydrogen fuel cell concept, two hydrogen multiple unit vehicles entered operation in September of that year, along a 100 km regional train track in Lower Saxony, Germany.[99] In 2017, a hydrogen-powered tram developed by China Railway Rolling Corporation (CRRC) began commercial operations in China's Hebei Province. In the vehicle, a 15-minute fueling session enables the vehicle to travel for 40 km at speeds of up to 70 kilometers/hour. In 2019, The San Bernardino County Transportation Authority (SBCTA) announced plans for the first domestic hydrogen fuel cell locomotive.

As with hydrogen fuel cell MDHD vehicles, the outlook for using hydrogen as a replacement for diesel is technologically feasible today. The major barriers are the high cost associated with upfitting the locomotives and the lack of hydrogen supply at competitive costs.

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[94] MBTA (2020) Rail Vision Alternatives 5 and 6. https://www.mbta.com/projects/rail-vision
[95] Alstom Communications. (2018). Coradia iLint: Alstom's zero-emission train. https://www.partners.alstom.com/Assets/View/92a183b6-b12a-4561-b356-76a587d0de4e
[96] Caltrain. (2019). Peninsula corridor electrification project (PCEP), JPB Board Meeting Q2, Quarterly Update #17 October 1 – December 31, 2018. Retrieved from Samtrans website: http://www.caltrain.com/projectsplans/CaltrainModernization/CalMod_Document_Library.html
[97] For example, Stockton California. (https://www.bnsf.com/news-media/railtalk/service/battery-electric-locomotive.html) and Germany (https://www.greencarreports.com/news/1127629_battery-powered-electric-trains-will-soon-bring-cleaner-air-especially-in-europe).
[98] Hydrogenics. (2018). HyPM-HD Power modules for light and heavy duty mobility. http://www.hydrogenics.com/wp-content/uploads/HyPM-HD-Brochure.pdf
[99] Alstom (2020) Coradia ILint – The World's First Hydrogen Powered Train. https://www.alstom.com/our-solutions/rolling-stock/coradia-ilint-worlds-1st-hydrogen-powered-train

7.2.3 Biofuels for Rail

Recently in California, the Capitol Corridor service is planning to test one of its newer, "Charger" locomotives on a renewable diesel.[100] At the same time, the agency will be collaborating with Caltrans (the California Department of Transportation) to perform lab testing of an older EMD F59 locomotive.[101]

7.3 Marine

Marine vessels operate at ports, along waterways, or off coastlines and include three broad categories of vessels: ocean-going vessels (OGVs), harbor craft, and recreational boats. The marine sub-sector accounts for under 1% of transportation emissions in the Commonwealth and has fluctuated over time.

7.3.1 Electrification and Hydrogen

Electrification of marine vessels appears to be primarily limited to passenger ferries. In 2018, Seattle announced it would convert its three largest ferries to electric.[102] In Norway, trips under 30 minutes are offered on battery electric-powered ferries.[103] In the San Francisco Bay Area, an 84-passenger, fuel cell electric ferry will begin operation in late 2020, with plans to expand to New York City waters next.[104] Another electrification opportunity is shore power – i.e., the use of landside electricity for power at berth – such as lights, pumps, communications, refrigeration – instead of running diesel auxiliary engines.[105] According to the EPA's Shorepower Emissions Calculator, use of shore power in the Commonwealth instead of an average diesel auxiliary engine reduces NO_x, SO_x, and CO_2 by 98%, 70%, and 60%, respectively.[106] Indeed there is a shore power project currently funded by MassDEP using the Volkswagen Settlement funding.[107] There is ongoing testing in the marine sector for fuel cell power packs, electric ships, and autonomous vessels.[108] There are opportunities for harbor craft to convert to alternative fuels such as LNG, use hybrid engines, and use fuel cell or battery electric propulsion systems.

A key barrier to electrification of marine vessels is the long lifetime of vessels.

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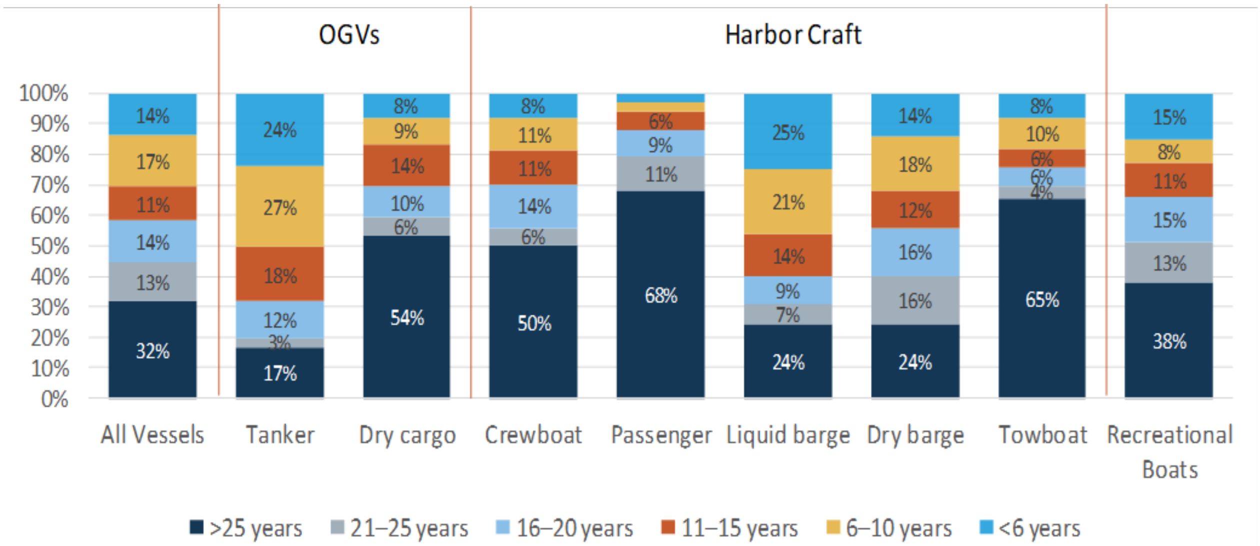
[100] Salian (2017) Renewable diesel use in California moves to fast track. https://www.sfchronicle.com/business/article/Renewable-diesel-use-in-California-moves-to-fast-12195892.php
[101] Kutrosky, D. (2019). Sustainable Practices at the Capitol Corridor: Strategies to Reduce Carbon-Based Fuel Emissions. Presented at the TRB Annual Meeting, Washington, DC.
[102] Seattle Times (2018) Washington State Ferries plans to convert its biggest vessels to electric power. https://www.seattletimes.com/seattle-news/transportation/washington-state-ferries-plans-to-convert-its-biggest-vessels-to-electric-power/
[103] Port of New York and New Jersey (2018) Progress to Cleaner Air. http://cleanports-nynj.com/wp-content/uploads/2018/06/HC-roadmap-053018.pdf
[104] Switch Maritime (2020). Homepage. https://www.switchmaritime.com/
[105] Port of Long Beach, CA (2020). Shower Power Page. https://www.polb.com/environment/shore-power/#shore-power-program-details
[106] EPA (2017) Shorepower Calculator. https://www.epa.gov/ports-initiative/shore-power-technology-assessment-us-ports (NEWE eGrid region used with any vessel type.)
[107] MassDEP (2019) Volkswagen Settlement Open Solicitation Grant Recipients. https://www.mass.gov/doc/list-of-volkswagen-settlement-open-solicitation-grant-recipients-december-2019/download
[108] Port of New York and New Jersey (2018) Progress to Cleaner Air. http://cleanports-nynj.com/wp-content/uploads/2018/06/HC-roadmap-053018.pdf

Figure 26 gives the age distribution vessels with the U.S. flag. This data comes from national statistics on marine freight from BTS.[109] As shown in the left-most column, almost a third (32%) of all marine vessels are more than 25 years old. This lack of turnover means the introduction of new technology into this sector is slower than other sectors and that vessels purchased in 2020 will possibly still exist in 2050.

Ammonia is viewed by many shipping experts as a promising alternative to fossil-based fuels.[110] There is no carbon emitted when burning ammonia. However, ammonia requires modifications to engine drive systems and only is one-third as energy dense as conventional diesel bunker fuel.

Figure 26. Average age of marine vessels in the United States, by vessel type.



[109] BTS (2018) US Flag Vessels by Type and Age. https://www.bts.gov/us-flag-vessels-type-and-age

[110] A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments Kyunghwa Kim 1,2,* , Gilltae Roh 1 , Wook Kim 2,* and Kangwoo Chun 1,2020, Journal of Marine Science and Engineering *